UNIVERSITY OF COPENHAGEN
FACULTY OF HEALTH & MEDICAL SCIENCES

Ph.D. Thesis

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Ph.D. Title

Investigation of special imaging studies
in patients with knee osteoarthritis

This thesis has been submitted to the Graduate School of Health and Medical Sciences, University of Copenhagen on the 9th November 2021

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Investigation of special imaging studies
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This Ph.D. thesis is based on the clinical research carried out from 2017 to 2021 at the Orthopaedic Hip & Knee Department, Gentofte Hospital.

1 Table of contents

2 Ph.D. amendment

This Ph.D. journey first started with the title:

Randomized clinical trial of medial unicompartmental versus total arthroplasty for medial tibiofemoral OA (March 2017).

It was amended to:

Investigation of special imaging studies in patients with knee osteoarthritis (November 2019).

The amendment was due to mainly COVID-19 related delay of a large-scale national RCT, which only recently finished including patients, and therefore no results are available yet.

3 Abbreviations

AMOA = Anteromedial Osteoarthritis

ICC = Intraclass Correlation Coefficient

JSW = Joint space width

mJSW = minimal Joint space width

MRi = magnetic resonance imaging

OA = Osteoarthritis

PPT = Pressure pain threshold

TKR= Total Knee Replacement

mUKR = Medial Unicompartmental Knee Replacement

WK = Weighted Kappa

X-ray = Radiographs

ΔLT = Delta Local tenderness

4 Funding and Conflict of Interest

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1. Gentofte Hospital, Orthopaedic department
2. Region Hovedstaden
3. DOS-foundation

5 List of Papers

I

Mortensen JF, Kappel A, Rasmussen LE, Østgaard SE, Odgaard A.

The Rosenberg view and coronal stress radiographs give similar measurements of articular cartilage height in knees with osteoarthritis.

-Published in Archives of Orthopaedic and Trauma Surgery, 3rd September 2021[1]

II

Mortensen JF, Mongelard KBG, Radev D, Kappel A, Rasmussen LE, Østgaard SE, Odgaard A.

MRi of the knee compared to specialized radiography for measurements of articular cartilage height in knees with osteoarthritis

-Published in the Journal of Orthopaedics, 12th May 2021[2]

III

Mortensen JF, Hald JT, Rasmussen LE, Østgaard SE, Odgaard A.

An investigation of medial tibial component overhang in unicompartmental and total knee replacements using ultrasound in the outpatient department.

-Published in the Journal of Knee Surgery, February 2021 [3]

6 English Summary

Knee Osteoarthritis is one of the leading causes of knee dysfunction due to debilitating pain and the deterioration of the knee's dynamics, which can lead to less activity and a lower quality of life. When conservative treatment has failed, surgery is possible by implanting a knee replacement, consisting of either a total knee or a partial knee replacement. This thesis focuses on the medial unicompartmental partial knee replacement (mUKR) and the total knee replacement (TKR), and the diagnostic imaging before and after surgery with these treatments.

The thesis has the following purpose:

Study I:

To evaluate if specialized radiographic techniques can assess articular cartilage height similarly by:

- Assessing the inter- and intrarater reliability and agreement of the Rosenberg view and both varus/valgus stress radiography.
- Comparing measurements of each relevant technique to each other.

Study II:

To assess whether MRi is a better diagnostic tool than specialized radiography in assessing articular cartilage height by:

- Assessing the interrater agreement of MRi.
- Comparing MRi to specialized radiography measurements.

Study III

-To investigate the association of tibial component overhang and local tenderness by:

- Assessing the reliability of ultrasound measurements of overhang on postoperative knee replacements.
- Comparing the incidence of overhang seen on postoperative radiographs to the overhang measured with ultrasound.
- Investigating correlations between overhang measurements and local tenderness.

Study I included seventy-three patients prospectively listed for either a mUKR or TKR, had double measurements of specialized radiography performed with the Rosenberg view and varus/valgus stress. Three knee surgeons measured articular cartilage height on each radiograph in the medial and lateral compartment over three rounds. The results showed substantial reliability and substantial to almost perfect inter/intrarater agreement. A strong to very strong correlation between the Rosenberg view and varus and valgus stress was found. This study concludes that the investigated techniques give similar measurements of articular cartilage height, allowing for the use of both techniques in the clinical setting. Using the Rosenberg view by itself makes it possible to save an extra radiograph and the accompanying radiation, along with the extra equipment and specialized personnel needed for a reliable, standardized stress radiography setup.

Study II included sixty patients from Study I, which also received an extremity MRi of the same knee. Two radiologists and one orthopedic surgeon measured articular cartilage height in the medial and lateral compartment on each MRi scan. These results proved fair to substantial interrater agreement. The medians of measurements were used to compare MRi to study I's median measurements of specialized radiography, which proved negligible to weak correlation medially, and strong to very strong correlation laterally. This study concludes that MRi should not replace specialized radiographs in the workup for mUKR.

Study III included sixty-four patients prospectively, where ultrasound and pressure pain thresholds, i.e., local tenderness, were measured. Measurements were performed at 5 or 10 different knee sites, depending on whether they had a mUKR or a TKR inserted, respectively. The use of ultrasound to measure tibial component overhang proved good reliability indicating its usefulness in the outpatient department. Comparison with conventional postoperative radiographs proved a systematic underestimation of overhang medially on radiographs, indicating that tibial component overhang measurements could be underreported. Finally, a positive correlation between overhang local tenderness was found, especially when located medially, which can irritate the medial collateral ligament.

This thesis investigates and highlights alternative specialized diagnostic tests within knee replacement surgery, helping to guide clinical decision-making and avoid unnecessary imaging and radiation, buying excess equipment, and ultimately higher costs per patient.

7 Dansk resume

Slidgigt i knæet er en af de mest almindelige årsager til knædysfunktion på grund af invaliderende smerter samt forværring af knæets dynamik, hvilket kan føre til nedsat aktivitet og lavere livskvalitet. Når konservativ behandling ikke lykkes, er kirurgi muligt ved at implantere en knæprotese, som kan bestå af en helprotese eller en delprotese. Denne afhandling fokuserer på delprotesen som kun udskifter den inderste del af knæet (mUKR) og helprotesen (TKR) som skifter hele knæet, samt diagnostiske metoder som kan bruges til billeddannelse i klinikken, både før og efter operation.

Afhandlingen har følgende formål:

Undersøgelse I:

At undersøge om specialiserede røntgen teknikker kan vurdere højden af ledbrusk ens, ved:

- Vurdering inter- og intrarater præcision og akkuratesse ved Rosenberg-view og både varus/valgus stress røntgen undersøgelser.
- Sammenligning af målinger af hver relevant teknik med hinanden.

Undersøgelse II:

At vurdere, om MR-scanning er et bedre diagnostisk værktøj end specialiseret røntgen til vurdering af ledbruskens højde, ved:

- Vurdering af MR-scannings interrater præcision og akkuratesse.
- Sammenligning af MR-scannings med specialiserede røntgen målinger.

Undersøgelse III:

At evaluere sammenhængen mellem udhæng af protese over knogle og lokal ømhed, ved:

- Vurdering præcision og akkuratesse af ultralydsmålinger af protesernes udhæng.
- Sammenligning udhæng set på postoperative røntgenbilleder med udhæng målt med ultralyd.
- Undersøgelse af sammenhænge mellem udhæng og lokal bløddelsømhed.

Undersøgelse I inkluderede treoghalvfjerds patienter, som var skrevet op til en mUKR eller TKR. Patienterne fik foretaget specialiseret røntgen, udført med Rosenberg-view og varus (hjulbenet)/valgus (kalveknæ)-stress. Tre knækirurger målte ledbruskhøjde i det mediale (inderste) og laterale (yderste) kammer i knæet, på hvert røntgenbillede, over tre runder. Resultaterne viste 'betydelig pålidelighed og væsentlig til næsten perfekt inter/intrarater overensstemmelse. Medianer blev brugt til at sammenligne de relevante teknikker, som viste stærke til meget stærke korrelationer. Denne undersøgelse viser, at de undersøgte teknikker giver lignende målinger af ledbruskhøjde, hvilket retfærdiggør brug af begge teknikker i den kliniske hverdag. Når man kun bruger Rosenberg-view, er det dog muligt at spare et ekstra røntgenbillede og den ledsagende stråling, samt det ekstra udstyr og specialiserede personale som der er behov for når der skal udføres pålidelig standardiseret stress røntgen.

Undersøgelse II inkluderede tres patienter fra studie I, som også fik lavet en MR-scanning af det samme knæ. To radiologer og en ortopædkirurg målte ledbruskhøjden for hver MRi -scanning. Disse resultater viste rimelig interrater overenstemmselse. Medianer blev brugt til at sammenligne MR-målinger med røntgen målinger fra Undersøgelse I, som viste ubetydelig til svag korrelation medialt og stærk til meget stærk korrelation lateralt. Denne undersøgelse konkluderer, at MR-scanning ikke bør erstatte specialiserede røntgenbilleder når man udvælger patienter som skal tilbydes mUKR.

Undersøgelse III inkluderede 64 patienter fremadrettet, hvor der blev udført ultralyd og måling af tryksmerter, dvs. lokal ømhed. Målinger blev udført på 5 eller 10 forskellige steder i knæet. Anvendelsen af ultralyd til måling af udhæng af protesen over knoglekanten viste god overensstemmelse, hvilket understreger dets anvendelighed ambulant. Sammenligning med konventionelle postoperative røntgenbilleder viste en systematisk undervurdering af udhæng medialt på røntgen, hvilket indikerer, at udhæng af knæprotesers kunne være underrapporteret. Endelig blev der fundet en positiv sammenhæng mellem udhæng og lokal ømhed, især når det befinder sig medialt, hvor det kan irritere nærliggende bløddele.

Denne afhandling undersøger og fremhæver alternative specialiserede diagnostiske tests inden for knæprotese kirurgi, hjælper med at guide klinisk beslutningstagning og at undgå unødvendige undersøgelser og stråling, køb af ekstra udstyr og i sidste ende højere omkostninger per patient.

8 Introduction

8.1 Background

8.1.1 -Knee Osteoarthritis and knee replacements

Knee Osteoarthritis (OA) is a degenerative disease that slowly breaks down the joint's articular cartilage and eventually other structures in the knee. On a global scale, knee OA is one of the leading causes of disability[6]. Knee OA can be debilitating with pain and decreased function and may require a knee replacement. By using artificial implants to replace the damaged knee joint, pain can be relieved, the knee function can be reestablished, and a better quality of life can be achieved [7, 8]. In many cases, there will be widespread degenerative changes of the knee. In these cases, it is necessary to insert a total knee replacement (TKR), replacing all the knee surfaces (see Figure 1A). However, there are cases in which OA is found only anteromedially, termed anteromedial osteoarthritis (AMOA). In these cases, it is possible to insert a partial implant termed a medial unicondylar knee replacement (mUKR) (see Figure 1B), where the femur's and tibia’s medial surfaces are replaced. The superior type of implant is still being debated and researched[9-11], but distinguishing between the implant choice for each patient is of utmost importance. This is

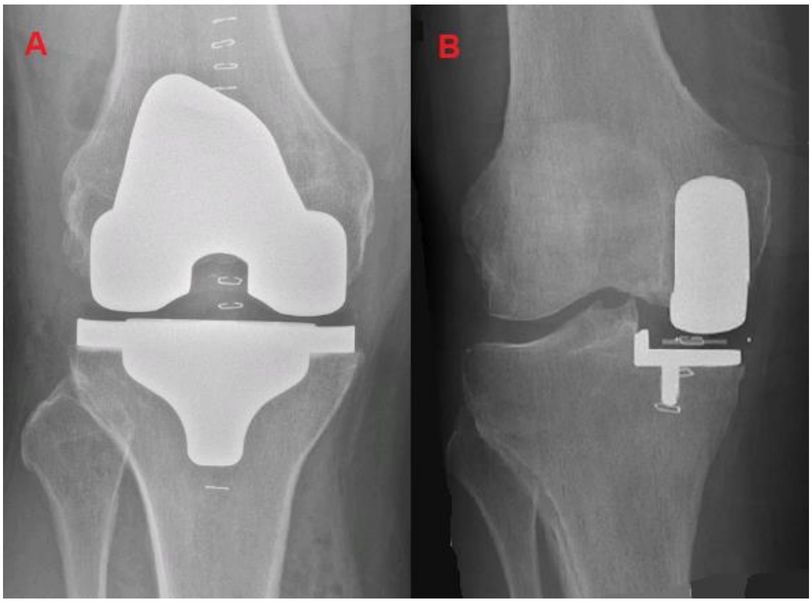

Figure 1 Radiograph of TKR (A) and mUKR (B), of patients from the studies.

typically primarily done radiographically, supported by clinical and intraoperative findings[12-14].
The prevalence of symptomatic knee OA in the Caucasian population is approximately 6% and increases to approximately 10% when age increases to above 65 years [15]. Studies report that severe radiographic changes affect 1% of people aged 25–34 and increase to nearly 50% in those 75 years and above[7].

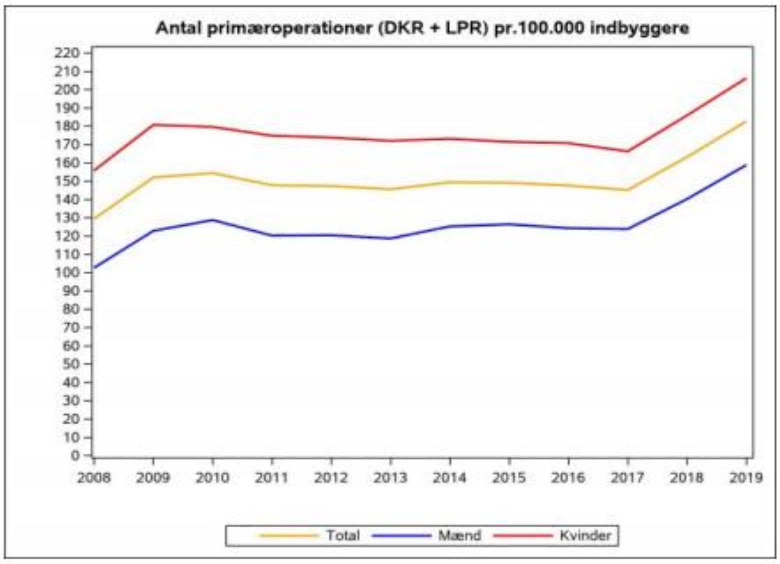

Figure 2 Incidence of primary knee replacements over the last 12 years. Source: Danish Knee Replacement Registry, copied with permission [4].

In Denmark, an incidence of 140-160 per 100.000 inhabitants have received a primary knee replacement in the years 2010-2018 (see Figure 2[4]). For international comparison, in the USA/Germany in 2011, approximately 304/206 primary knee replacements per 100.000 inhabitants were performed, respectively [16]. On a global scale, the incidence of knee OA is increasing [17, 18], in part due to an aging population and rising obesity[19], resulting in an expected increase in the volume and demand for knee replacements [20]. Patient demand for better outcomes and increased expectations after knee replacement are also on the rise, while cost-effectiveness is increasing in all healthcare systems globally. Therefore, it is important to highlight the capabilities and limits of different clinical diagnostic devices and techniques to ensure the correct imaging techniques and most value for money is obtained in the diagnostic imaging process per patient.

8.2 -Diagnostic imaging

8.2.1 – **Radiography**

Radiography (X-ray) has been used since the 1950's in assessing the presence of OA (see figure Figure 3) in knees [21], and many other knee-specific radiographic techniques have been introduced since then [22]. Conventional radiography of the knee, apart from the lateral view, consists of a weight-bearing anteroposterior radiograph, with the knees in their natural anatomical position[23, 24]. Previously, often a non-loading/non-weight-bearing image would be used, but Ahlbäck demonstrated the value of loaded/weight-bearing images [22].

Figure 3 Conventional radiographic Anteroposterior method, of an x-ray image with a normal joint space (A), and an x-ray image of a patient with knee OA in the medial (innerside) compartment (B).

X-ray is considered the gold standard for diagnosing osteoarthritis (OA) [13] in terms of measuring the articular cartilage thickness [22, 25, 26].

Rosenberg et al. introduced a new radiographic method in 1988. The knee is in 45° flexion, which proved to be more sensitive than the aforementioned conventional X-ray images, where the knee only has a slight flexion [27]. In 1986, Goodfellow et al. introduced coronal stress X-ray to further investigate the knee under a higher load in each compartment, done manually (or with instrumentation) by stressing the knee in varus or valgus [25].

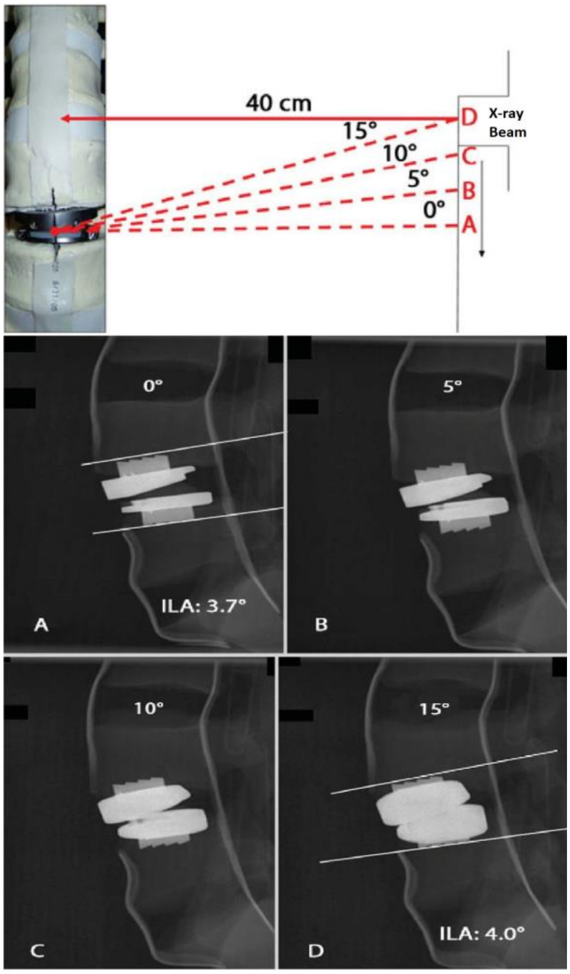

Figure 4 (Above) Radiograph of spine surgery on sawbone with disc-replacement, with the X-ray beam in neutral position (A), at 5°(B), 10°(C), and 15° (D). (Below) X-ray images showing the parallax effect increase from A to D.

Permission granted for reference [5] via Open access terms from Spine Arthroplasty Society.

These knee position manipulation methods and the X-ray beam angle can give the clinician very specific information about certain areas of interest. Though, if there are multiple areas of interest, additional specialized X-rays are necessary. Clinical examination of the knee isn't sensitive enough by itself to detect osteoarthritis, which necessitates X-rays to keep its place in knee OA diagnostics.

The **advantages** of using standard X-ray include quick execution and relatively low cost. These benefits fade when multiple specialized radiographs, which are more expensive than standard radiographs, are necessary for further diagnostics. Specialized radiography often includes extra equipment to be purchased, extra time for setup, and skilled radiographers to carry out.

Another disadvantage of X-ray is the parallax effect, a rotational projection phenomenon that can be present when imaging in 2 dimensions [28]. This effect is part of an umbrella term of a visual illusion. The first phenomenon of these visual illusions is the artifacts and oddities in the method that images are generated, and the second is the method of processing in the brain. When using radiographs to help make important decisions, clinicians should be aware of this effect, visually presented in Figure 4[5], from another subspecialty of Orthopedic surgery (Spine surgery). A clear distortion of the X-ray image is produced for every 5 degrees of possible error in the X-ray beam, depending on the area of interest a clinician wishes to inspect.

The Rosenberg view [27] and coronal plane stress X-ray are suggested in various radiographic algorithms to guide surgeons' choice between offering a mUKR or TKR [12-14]. It is essential to know the distribution of degenerative disease in each knee compartment when considering a medial unicompartmental knee replacement. It is important to know how different X-ray techniques discriminate between degenerative disease levels in each knee compartment to ensure the correct knee replacement for each patient. For this reason, this thesis is partly focused on specialized radiography, including the Rosenberg view and varus/valgus coronal stress radiography.

Other imaging techniques, such as Ultrasound (US)/Computertomografi (CT)/Magnetic Resonance (MRi), are also available to avoid this effect and excessive X-ray radiation exposure. Still, they also have their benefits and pitfalls.

8.2.2 – **MRi**

Magnetic Resonance imaging (MRi) has long been considered a gold standard for evaluating soft tissue, articular cartilage, and early osteoarthritic changes. Still, the usefulness in detecting severe OA is less clear [29, 30]. It has generally not become a standard screening tool in the decision-making process within knee arthroplasty surgery in clinical practice. This is primarily due to pricing and time consumption in healthcare systems where saving costs and improving efficiency are high priorities. Although, some areas of the world see an increasing trend in the overuse of MRi for end-stage knee OA [31].

In Denmark, MRi is currently not considered to have a justified place in the knee OA diagnosis and for the guidance of implant choice [15, 32]. The Danish national clinical guidelines suggest that MRi should be retained for differential diagnostics and not to diagnose widespread or isolated knee OA [32]. MRi has been criticized in the screening process for knee replacements, especially due to knee pathology overestimation [33].

Tendencies seen in other countries of increased usage of MRi for knee OA diagnostics are not desirable, as MRi is an expensive and time-consuming imaging technique. MRi is a feasible option for most patients, but several patient groups can present with contraindications of having an MRi performed. Such patients can present with metallic implants like pacemakers or claustrophobia[34].

MRi is available in different spatial imaging qualities, depending especially on the field level of tesla and the imaging resolution, allowing for a thorough inspection of the whole knee and avoiding radiation exposure to the patient. This raises the question of whether the cost justifies the extra information received from this expensive imaging technique.

More recently, less expensive and quicker MRi scanners have been introduced and upgraded through the years, producing lower resolution imaging from lower field levels of tesla. An example of this is an extremity MRi-scanner, which is the focus of comparison to radiographs in this thesis.

8.2.3 – Ultrasound

Ultrasound (US) has presently had a limited place in orthopedic surgeons' hands and has mostly been used by experienced radiologists. Newer technology, including better probes, transducers, and better imaging quality, allows less experienced clinicians to use the US more effectively. It is radiation-free and completely safe for all types of patients. US has been demonstrated to suggest the early presence of knee OA [35] and can also visualize osteophytes [36]. But scarce information is present in the literature regarding evaluating end-stage OA and postoperative knee replacements with US imaging.

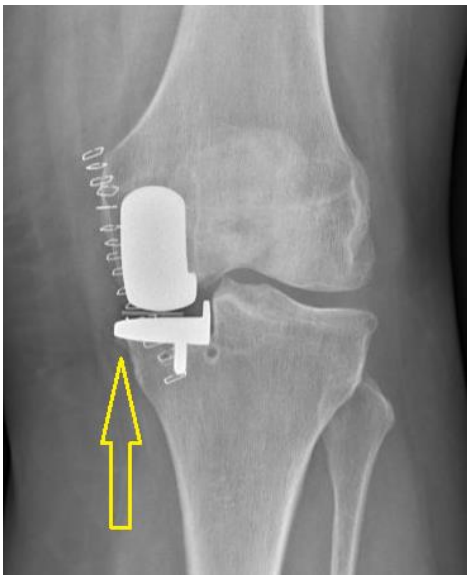

Figure 5 Examples of clear radiographic overhang of a mUKR on the medial side of the knee

The benefits of using US are the relatively low cost, quick imaging of the area of interest, and the complete safety for any patients being examined. The disadvantages of using US are observer-dependency and lack of general formal education in using US in clinical practice. The future of US has many possibilities, especially with the heightened technology, user-friendliness, and easier interpretation of quality images produced. The main question is when and where it would be most relevant to implement the use of US for knee OA patients.

Is it possible to post-operatively assess the inserted metal components' placement and maybe bypass the possible parallax effect of radiography, i.e., a rotational projection phenomenon (as seen in Figure 4)? It could be useful in considering whether the knee replacement is oversized, malrotated, or misplaced. Its edge can identify this, creating an ”overhang” over the bone cortex, as seen on radiographs in Figure 5. This overhang may, in turn, lead to medial or lateral knee pain [37-40]. This thesis will focus on ultrasounds' capability to measure the tibial component overhang of a knee replacement, which may be overlooked on conventional radiographs, and whether the overhang measured has consequences such as local tenderness.

8.3 Objectives

<u>The overall aim of the thesis</u>

The purpose of this thesis is to investigate specialized radiographic techniques, compare them to MRi, and investigate Ultrasound and compare it to conventional postoperative radiography.

<u>Study I + II</u>

These studies' objectives are to investigate if different specialized radiographic techniques and MRi can measure articular cartilage height similarly.
The specific study aims: 1) To analyze the test-retest reliability of the Rosenberg view and coronal stress radiography in a cohort of patients with knee osteoarthritis. 2) To assess the inter- and intrarater agreement for the radiographic methods and MRi. 3) To investigate the precision and accuracy of these techniques. 4) To investigate if the Rosenberg view can determine joint space width similar to coronal stress radiography. 5) To assess if the measurements of specialized radiographic techniques are similar to MRi.

<u>Study III</u>

This study aims to investigate whether US-measured tibial component overhang is associated with local tenderness.
Specific study aims include: 1) Investigating the reliability of ultrasound measurements of tibial component overhang. 2) Comparing ultrasound measured overhang to conventional postoperative radiographs. 3) To assess correlations between the overhang and local tenderness.

9 Methods

9.1 -Study design and population

Study I + II

These studies were designed as prospective level III diagnostic studies, investigating a diagnostic test [41]. Guidelines for reporting reliability and agreement studies (GRRAS) were followed [42]. One hundred and sixty patients were invited to participate in these studies at a high-volume knee arthroplasty unit after being listed for a mUKR/TKR. Seventy-three patients were included from August 2018 to June 2019, and they all had specialized radiographs taken. Eighty-seven declined participation. Of the included seventy-three patients, sixty received an MRi scan of the same knee, constituting the population of Study II. Flowcharts can be seen in Figure 6[1, 2], and inclusion/exclusion criteria can be seen in Table 1.

Study III

This study was a prospective Level II prognostic study, investigating the effect of a patient characteristic on specific patient outcomes [41]. Sixty-four patients (64 knees) were prospectively included from July 2018 to May 2019 for their 3-month mUKR/TKR follow-up, shown in Figure 6.

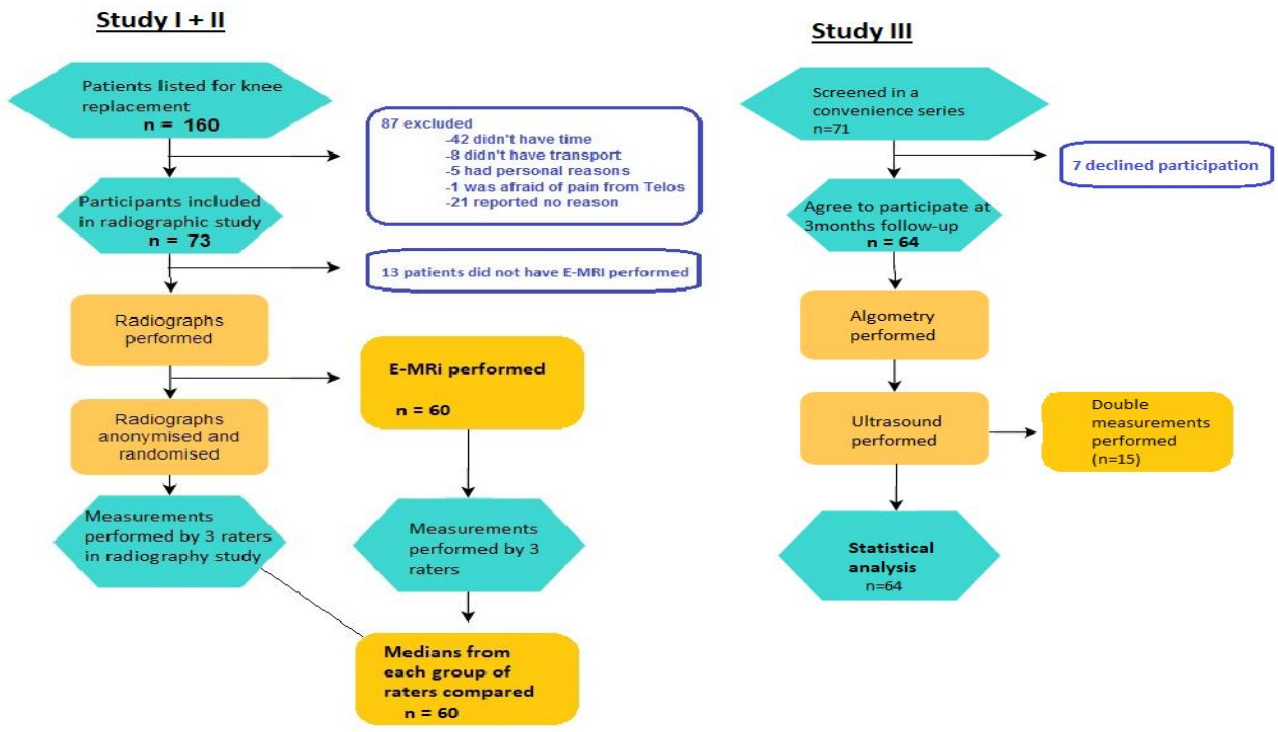

Figure 6 Flowcharts of all studies.

Copied from reference [1-3], with permission from Springer Nature, Elsevier and Thieme publishing, respectively.

	Specialized X-ray (I)	MRi (II)	US (III)
Inclusion Criteria	-Listed for mUKR/TKR.	Specialized radiographs were performed in Study I.	-Received a mUKR/TKR and present for their 3-month follow-up.
Exclusion Criteria	-Pregnancy -Severe systemic disease, -Employment at the department -Compliance issues	-Contraindications for performing MRi, such as: -Metallic implants -Pacemaker -Claustrophobia	None

Table 1 Inclusion and exclusion criteria for all three studies (I-III).

9.2 Imaging techniques

Study I + II

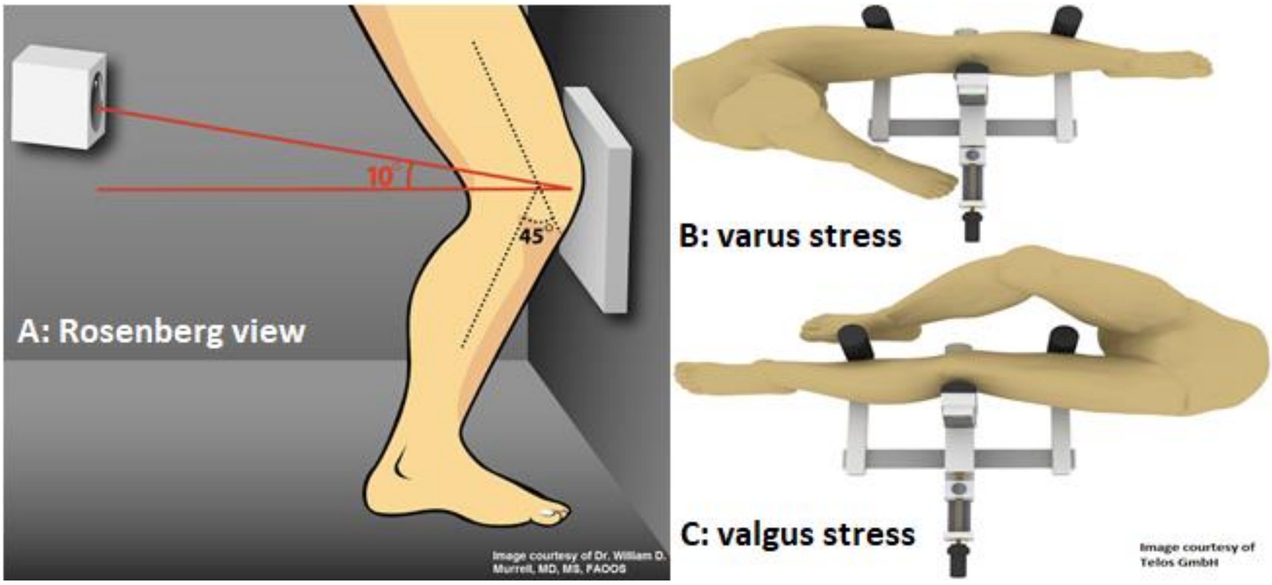

Figure 7 Method of Rosenberg (A), Telos Varus stress (B), and Valgus stress radiography (C).

Copied from reference[1], with permission from Springer Nature publishing.

Rosenberg View

Patients were positioned with full weight-bearing evenly divided on each lower extremity. The knees were in equal flexion at 45°. The angle between the femur and tibia in relation to the X-ray cassette was evenly distributed. A posteroanterior X-ray beam with a 10° caudal inclination was used (see Figure 7A[1, 43]).

Coronal Stress

Patients were positioned supine with a 20-30° flexed knee with a supportive triangular pillow to relax the muscles around the knee and the posterior capsule [25]. A commercially available stress device from Telos (Telos GmbH, Hungen – Obbornhofen, Deutschland) was used. The Telos stress device was first positioned in either varus (see Figure 7B) or valgus stress (and Figure 7C) and, after that, switched. The X-ray beam was pointed 5° caudally, approximately 1 cm below the patella. All radiographs were performed with a 25mm steel ball placed at a level consistent with the middle of the knee joint to allow for calibration.

MRi

MRi scans were obtained using an Optima MR 430s 1,5 T extremity MRi scanner (see Figure 8). The patients were positioned in a reclining sitting chair outside of the scanner. The knee was positioned in the coil with 0-5° flexion, and only the patients' knee was placed inside the scanner. Coronal and axial plains of proton density-weighted sequences with and without fat saturation were produced, with a slice thickness of 3.5mm/4.5mm, respectively. Images were obtained without weight-bearing as it was not feasible, and it has proven to show similar cartilage thickness as weight-bearing MRi [44].

Figure 8 Method of MRi scan, with extremity scanner

Source: GE Healthcare, permission acquired for use of image.

Study III

Algometry and pressure pain threshold

Patients were positioned semi-recumbent with 90° flexed knee when performing algometry. A validated self-assembly pressure algometer was used [45] (see Figure 9A). The knee joint and tibial component were palpated to localize 5 or 10 different measurement sites for UKR or TKR, respectively (see Figure 10[3]). Pressure pain threshold (PPT) was measured in kg/cm² at these sites. For easier interpretation, this pressure-induced pain level was termed local tenderness in this Study.

Figure 9 Methods of measurement of PPT (A), and Ultrasound measurement at the same sites (B)

Ultrasound

Patients remained in the same position as the algometric measurements, and US was performed at the same sites (see Figure 9B). A Sonosite M-Turbo (Fujifilm Sonosite, Inc., WA, USA), using the musculoskeletal probe (HFL38X) with a frequency of 13-6MHz, was used. Fifteen patients were measured by one other rater to allow for agreement analysis. Second-round measurements were conducted without prior knowledge of the first-round measurements.

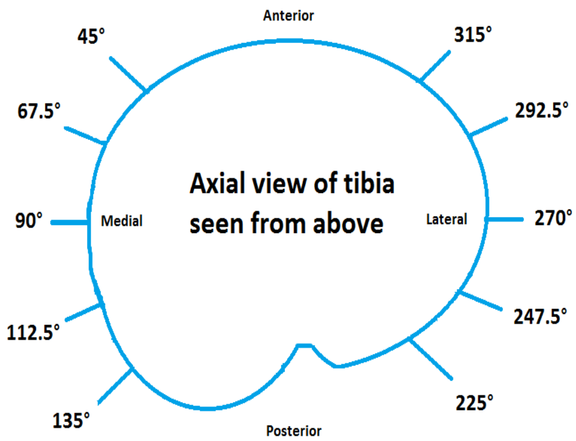

Figure 10 Axial representation of tibia from above, showing 5 to 10 sites of measurement for UKA and TKA, respectively.

Copied from reference[2, 3], with permission from Thieme publishing, respectively.

Conventional radiography

Conventional postoperative radiographs were analyzed in conjunction with the patient's follow-up. We used the spherical stem distally in TKR's for calibration. In UKR's, we used either the tibial baseplate or the femur shield in the AP-view.

9.3 Measurements:

Study I + II

Radiographs

Radiographs were magnification calibrated (with a 25mm steel ball), anonymized, and randomly ordered using the Impax-Orthopaedic-Tools program (Agfa-Gevaert, Mortsel, Belgium), Syngo.via Client software (Siemens Healthcare GmbH, Erlangen, Germany), and K-PACS workstation Version 1.0.1 (Image Information Systems Europe GmbH, Rostock, Germany). Three experienced knee surgeons performed measurements over three rounds, with a minimum of 2 weeks between each round (See flowchart in Figure 6)

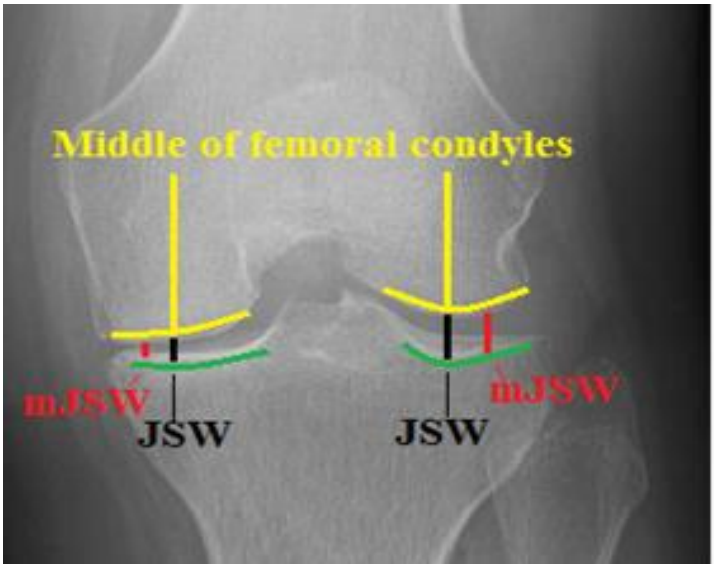

Figure 11 Radiographic measurement technique of JSW and mJSW of both Rosenberg and Varus/Valgus stress views.

Copied from reference [1, 2], with permission from Springer Nature and Elsevier publishing, respectively.

Joint space width (JSW) and minimal joint space width (mJSW) were measured (millimeters) in the medial and lateral tibiofemoral compartments of the knee [46]. JSW was measured as a standardized location at the middle point of each femoral condyle perpendicularly to the tibial plateau. mJSW was measured to be the smallest perceived joint space width on weight-bearing surfaces in each compartment (see Figure 11 [1, 2]).

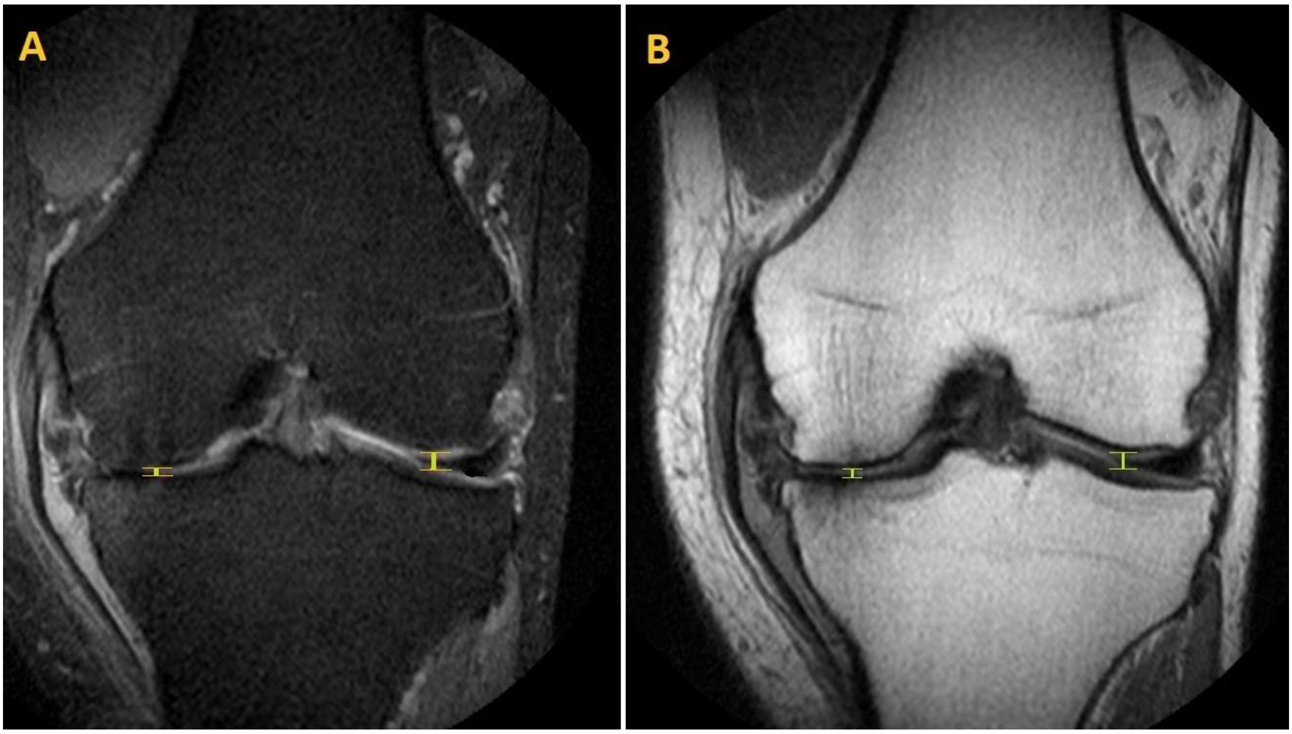

Figure 12 MRi scanning using PD-FSE imaging with fat saturation (A) and without fat saturation (B), showing the standardized central measurement of the articular cartilage height in the tibiofemoral joint medially and laterally, measured as JSW.

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MRi

MRi scans were reviewed on IMPAX Site working station 6.6.1.8006 (Agfa-Gevaert, Mortsel, Belgium) by three raters consisting of a consultant musculoskeletal radiologist, a radiology resident, and an orthopedic resident. Articular cartilage height was measured in the medial and lateral tibiofemoral compartment. Each knee compartment was assessed by measuring as centrally as possible between the femoral condyle and tibial plateau. This decided location was aided by axial visualization, and the measurement was considered the standardized location of JSW. Measurements were also performed as the smallest distance perceived (mJSW) between the femoral and tibial cortex at a weight-bearing location, as shown in Figure 12.

Study III

Ultrasound

The distance from the tibial component's outer edge to the bone surface was measured in millimeters (see Figure 13A). The overhang was recorded for each patient at all relevant sites. The largest overhang was recorded both laterally and medially to compare to conventional radiography to investigate the possible presence of a parallax effect.

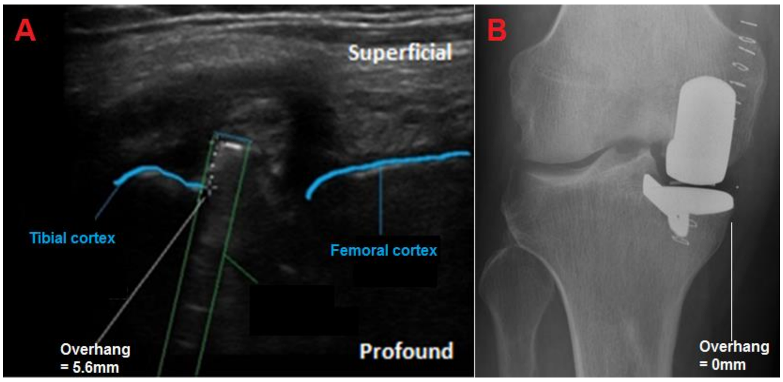

Figure 13 Figure A - Ultrasound measurement at 112.5 ° posteromedial, where blue is seen as the bone cortex, green as the tibial component, and white is the measurement of the overhang. Figure B Radiograph of the same patient as seen in Figure A, where no overhang is seen medially. Rotation of the radiograph and tibial component are both seen and create uncertainty of the extent of overhang.

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Conventional radiography

The overhang was measured medially and laterally (only TKR) on calibrated conventional postoperative radiographs (see Figure 13B). This was done on calibrated images, with overhang measured from the tibial component's outer edge to the bone surface, as with US. The same software as in Study I + II was used.

Local tenderness

Defining local tenderness required several steps:

First, to quantify each patient's local tenderness at different knee sites, the pressure pain threshold was measured [45, 47] by recording the amount of pressure required to elicit a sensation of pain. The measurements were performed at all relevant sites (see Figure 10) and were recorded in kg/cm².

Secondly, to account for the subjectivism of pain perception[48], mean measurements of PPT at sites with **no overhang** were considered to be the best expression of baseline tenderness.

Thirdly, sites with **no overhang** and sites with **maximal overhang** were assessed for mean differences in PPT (paired t-test), showing a mean difference of 1.3kg/cm² (CI 1-2; p=0.001). This proving more tenderness at sites with **maximal overhang** than at sites with **no overhang**. To put this quantification into perspective, approximately 4kg/cm² is enough pressure to whiten the examiner's nail bed of the fingertips when performing palpation [49].
Lastly, we found the difference of local tenderness of sites with **no overhang** and the site with **maximal overhang**, defining a new variable: ΔLocal tenderness (ΔLT).

$$\Delta LT = \textit{Mean PPT (sites with no overhang)} - \textit{PPT (maximal overhang)}$$

The rationale behind the establishment of this variable is found illustrated in Figure 14.

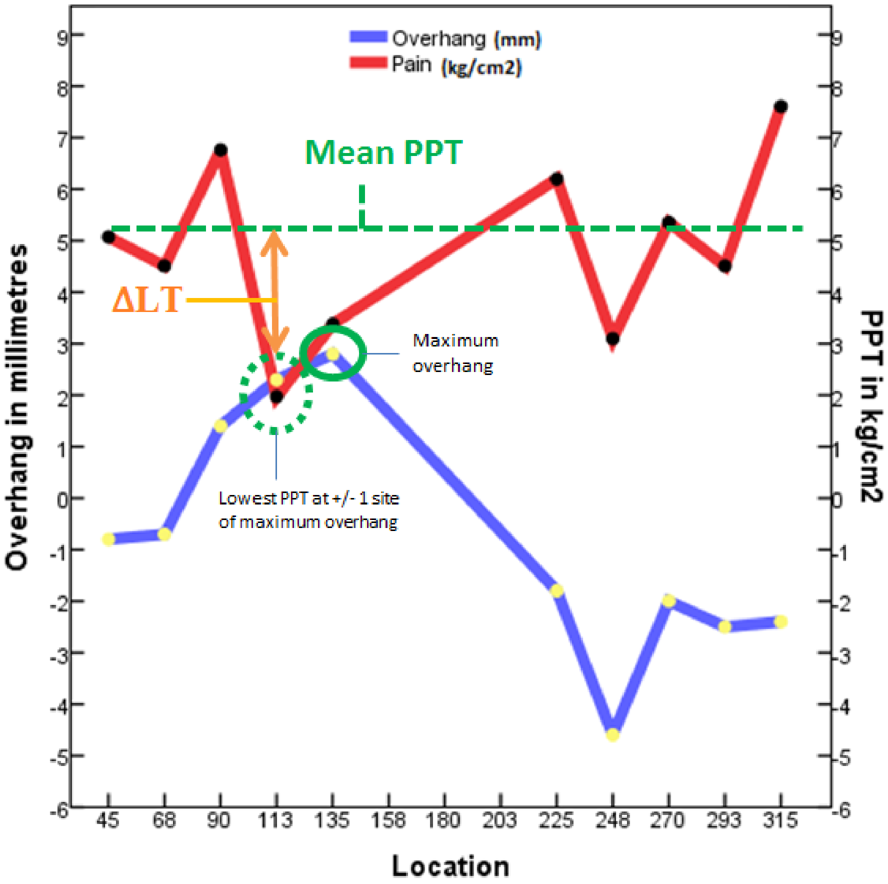

Figure 14 Example of one patients' measurement, and the deductive reasoning behind the establishment of the variable, ΔLocal tenderness.

9.4 Statistical analysis

<u>All studies:</u>

Statistical analyses were performed with SPSS statistical package version 22 (IBM SPSS Inc, Chicago, IL) and Microsoft Excel (Microsoft Corporation, Washington, USA) with Realstatistics-data-analysis-tool add-in.

Patient demographics were compared using the Student’s T-test.

A comparison of means between techniques was made using the paired T-test.

Strength of reliability, agreement, and relationships are categorized as seen in Table 2.

As the GRAAS guidelines require, either a combination of coefficients should be reported, or graphical methods should accompany single summary reproducibility measures. We chose to complement our results with Bland Altman plots with the mean difference (accuracy) and limits of agreement (precision) [50], and for some analyses, scatterplots to visualize the distribution [42].

Strength of reliability & agreement for Weighted Kappa [51]		Strength of reliability & agreement for ICC [52]		Strength of relationship for Correlation coefficients [53]	
Poor	< 0	**Poor**	< 0.5	**Negligible**	0-0.1
Fair	0-0.2	**Moderate**	0.5-0.75	**Weak**	0.1-0.39
Moderate	0.21-0.4	**Good**	0.75-0.9	**Moderate**	0.4-0.69
Substantial	0.61-0.8	**Excellent**	0.9-1	**Strong**	0.7-0.89
Almost Perfect	0.81-1			**Very Strong**	0.9-1

Table 2 Statistical categorizations of different statistical methods.

Study I & II:

Linear Weighted Cohen's Kappa (WK) with a 95% confidence interval for agreement and reliability analysis was used in Study I and II due to zero-limited data, which created a floor effect and imposed difficulties in using parametric statistical analysis.

Spearman's rank correlation coefficient was used due to data not being normally distributed as mentioned above.

Study III:

Tests of normality were performed using Kolmogorov-Smirnov test.

Agreement of ultrasound measurements was calculated using the Intraclass Correlation Coefficient (ICC).

Pearson correlation coefficient was used due to normally distributed data to investigate associations.

Subgroup analyses were performed using the Wilcoxon signed-rank test.

9.5 Ethical considerations

Study I + II

The Danish Health Research Ethics committee approved this thesis's first two studies (Videnskabsetisk komite, VEK), with Journal-nr: H-18010291. Each participant gave written consent.

Study III

The Danish Health Research Ethics committee did not deem this Study necessary for ethics approval, as there was no radiation and intervention to the participants, and participants gave informed consent.

10 Summary of Results

10.1 Patient demographics

	Study I	Study II	Study III
Age (years)	73 ± 8.1	71 ± 8	69.8±8.1
BMI (kg/m2)	28.1 ± 4.6	28 ±4	29.0±4
UKR (n)	29	27	32
TKR (n)	44	33	32
Females (n)	35	31	32
Males(n)	38	29	32
Total (n)	73	60	64

Table 3 Patient characteristics. There were no differences in age and BMI between sexes and implant types in all studies.

Study I

The mean age of patients was 73 (8.1) years, with no difference between sexes (p = 0.23) and implant types (*p* = 0.26). The mean BMI was 28.1 (4.6) kg/m², with no difference between sexes (*p* = 0.45) or implant types (*p* = 0.88) [1].

Study II

The mean age of patients was 71 (8) years, with no difference between sexes (p = 0.9) and implant types (p = 0.4). The mean BMI was 28 (4) kg/m², with no difference between sexes (p = 0.4) and implant types (p = 0.5)[2].

Study III

The mean age of patients was 69.8 (8.1) years, with no differences between sexes (p = 1) and implant types (p = 0.2). The mean BMI was 29 (4) kg/m², with no difference between sexes (p = 0.1) and implant types (p = 1)[3].

An overview of patient characteristics can be seen in Table 3.

10.2 Reliability and agreement

Study I's results are summarized in Table 4[1], followed by Study II's results in Table 5[2] below and strength categorization for all studies is summarized above in Table 2.

Study I:

The Rosenberg view proved substantial test-retest reliability in both medial (WK: JSW 0.71 / mJSW 0.74) and lateral compartments (WK: JSW 0.66 / mJSW 0.63). Intrarater agreement was shown to be substantial to almost perfect medially (WK: JSW 0.7-0.89 / mJSW 0.85-0.92) and moderate to substantial laterally (WK: JSW 0.74-0.80 / mJSW 0.59-0.77). Interrater agreement was shown to be similar for the intrarater analysis both medially (WK: JSW 0.73-0.77 / mJSW 0.77-0.83) and laterally (WK: JSW 0.63-0.68 / mJSW 0.42-0.60)[1].

Varus stress radiography showed substantial reliability in the medial compartment (WK: JSW 0.71 / mJSW 0.73), and moderate reliability laterally (WK: JSW 0.54 / mJSW 0.45). Intrarater agreement showed substantial to almost perfect agreement medially (WK: JSW 0.75-0.81 / mJSW 0.78-0.86), and moderate to substantial agreement laterally (WK: JSW 0.66-0.77 / mJSW 0.47-0.62). Interrater agreement proved substantial agreement in the medial compartment (WK: JSW 0.68-0.79 / mJSW 0.73-0.79), although only fair to moderate agreement laterally (WK: JSW 0.32-0.52 / mJSW 0.26-0.43)[1].

Valgus stress radiography proved substantial reliability in the medial compartment (WK: JSW 0.58 / mJSW 0.51) and in the lateral compartment (WK: JSW 0.69 / mJSW 0.69). Intrarater agreement showed substantial agreement medially (WK: JSW 0.71-0.8 / mJSW 0.62-0.75) and also laterally (WK: JSW 0.51-0.75 / mJSW 0.69-0.77). Interrater agreement was found to be moderate to substantial medially (WK: JSW 0.65-0.7 / mJSW 0.59-0.69) and laterally (WK: JSW 0.63-0.66 / mJSW 0.5-0.64)[1].

Study II:

MRi proved fair to substantial interrater agreement medially (WK: JSW 0.46-0.64 / mJSW 0.38-0.62) and moderate to substantial agreement laterally (WK: JSW 0.44-0.53/mJSW 0.46-0.61)[2].

Study III:

Ultrasound measurements of overhang proved good reliability with an ICC of 0.83-0.88, both on the tibial component's medial and lateral side[3].

Rosenberg												
	Medial JSW			Medial mJSW			Lateral JSW			Lateral mJSW		
Intrarater												
Rater	1	2	3	1	2	3	1	2	3	1	2	3
WK	0,89	0,78	0,86	0,88	0,85	0,92	0,80	0,74	0,80	0,71	0,59	0,77
CI	0,84-0,93	0,70-0,85	0,79-0,92	0,83-0,93	0,79-0,92	0,86-0,97	0,70-0,89	0,65-0,82	0,72-0,88	0,60-0,82	0,45-0,72	0,68-0,86
Interrater												
Rater	1vs2	1vs3	2vs3	1vs2	1vs3	2vs3	1vs2	1vs3	2vs3	1vs2	1vs3	2vs3
WK	0,77	0,76	0,73	0,77	0,83	0,79	0,63	0,67	0,68	0,45	0,60	0,42
CI	0,69-0,86	0,67-0,85	0,65-0,82	0,67-0,87	0,75-0,91	0,70-0,87	0,51-0,76	0,54-0,79	0,57-0,79	0,32-0,58	0,47-0,72	0,28-0,55
Test-retest												
WK	0,71			0,74			0,66			0,63		
CI	0,66-0,76			0,69-0,79			0,60-0,73			0,56-0,69		

Varus Stress												
	Medial JSW			Medial mJSW			Lateral JSW			Lateral mJSW		
Intrarater												
Rater	1	2	3	1	2	3	1	2	3	1	2	3
WK	0,81	0,75	0,81	0,86	0,80	0,78	0,77	0,70	0,66	0,51	0,47	0,62
CI	0,73-0,90	0,66-0,85	0,74-0,88	0,78-0,93	0,70-0,89	0,70-0,86	0,69-0,85	0,60-0,79	0,55-0,76	0,39-0,63	0,35-0,60	0,50-0,74

Table 4 Weighted Kappa, with 95% confidence interval, of medial JSW/mJSW and lateral JSW/mJSW. Intrarater, Interrater agreement and test-retest reliability were calculated.

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Interrater												
Rater	1vs2	1vs3	2vs3	1vs2	1vs3	2vs3	1vs2	1vs3	2vs3	1vs2	1vs3	2vs3
WK	0,79	0,72	0,68	0,79	0,77	0,73	0,32	0,49	0,52	0,43	0,34	0,26
CI	0,70-0,88	0,62-0,81	0,58-0,77	0,70-0,87	0,66-0,87	0,62-0,83	0,20-0,44	0,34-0,64	0,40-0,65	0,30-0,55	0,20-0,48	0,13-0,38
Test-retest												
WK	0,71			0,73			0,54			0,45		
CI	0,65 - 0,77			0,47 – 0,62			0,67 – 0,79			0,37 – 0,52		
Valgus Stress												
	Medial JSW			**Medial mJSW**			**Lateral JSW**			**Lateral mJSW**		
Intrarater												
Rater	1	2	3	1	2	3	1	2	3	1	2	3
WK	0,80	0,71	0,73	0,75	0,62	0,73	0,51	0,71	0,75	0,70	0,69	0,77
CI	0,73-0,87	0,62-0,80	0,64-0,82	0,66-0,84	0,51-0,73	0,64-0,83	0,36-0,65	0,61-0,80	0,66-0,84	0,58-0,82	0,58-0,80	0,68-0,85
Interrater												
Rater	1vs2	1vs3	2vs3	1vs2	1vs3	2vs3	1vs2	1vs3	2vs3	1vs2	1vs3	2vs3
WK	0,69	0,70	0,65	0,64	0,69	0,59	0,63	0,65	0,66	0,51	0,64	0,50
CI	0,59-0,79	0,59-0,81	0,55-0,75	0,52-0,77	0,59-0,79	0,44-0,73	0,52-0,74	0,53-0,77	0,54-0,77	0,38-0,65	0,51-0,77	0,37-0,64
Test-retest												
WK	0,58			0,51			0,69			0,69		
CI	0,51 – 0,64			0,43 – 0,58			0,63 – 0,75			0,63 – 0,75		

Table 4 continued

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MRi interrater agreement						
	Medial JSW			Medial mJSW		
Raters	1vs2	1vs3	2vs3	1vs2	1vs3	2vs3
WK	0,61	0,46	0,64	0,44	0,38	0,62
CI	0,51-0,71	0,34-0,59	0,52-0,76	0,26-0,63	0,17-0,59	0,45-0,8
	Lateral JSW			Lateral mJSW		
Raters	1vs2	1vs3	2vs3	1vs2	1vs3	2vs3
WK	0,47	0,44	0,53	0,46	0,47	0,61
CI	0,32-0,61	0,3-0,58	0,42-0,64	0,31-0,6	0,34-0,6	0,49-0,72

Table 5 Weighted Kappa, with 95% confidence interval, of MRi interrater agreement in the medial JSW/mJSW and lateral JSW/mJSW.

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10.3 Rosenberg view vs. Coronal stress radiography

Strong to very strong correlation was found between these techniques in their respective compartment (medial r = 0.81-0.91; lateral r = 0.79-0.83), also visualized with scatterplots (see Figure 15A+C+E[1]). The categorization of strength can be seen above in Table 2.

Mean differences between the Rosenberg view and varus stress were found in medial compartment JSW/mJSW of respectively 0.07 (0.82) mm/0.21 (0.88) mm (p = 0.45/0.45). Between Rosenberg view and valgus stress, mean differences of 0.62 (1.1)mm/0.45 (1.1)mm were found (p = 0.0001/0.001), showing valgus stress measuring lower cartilage height (visualized in Figure 15E+F[1]). Bland Altman plots show mean differences close to zero, as seen in Figure 15, indicating similar accuracy for all techniques. It is apparent that some patients are measured to zero mm JSW/mJSW, while up to 2mm with the comparative technique, but this is relatively evenly distributed between both sides.

Most Bland Altman plots showed acceptable limits of agreement. Although, in the lateral compartment, limits of agreement showed measurements of -1.6 to 2.6mm, in favor of valgus stress measuring slightly lower height, indicating less similar precision between techniques.

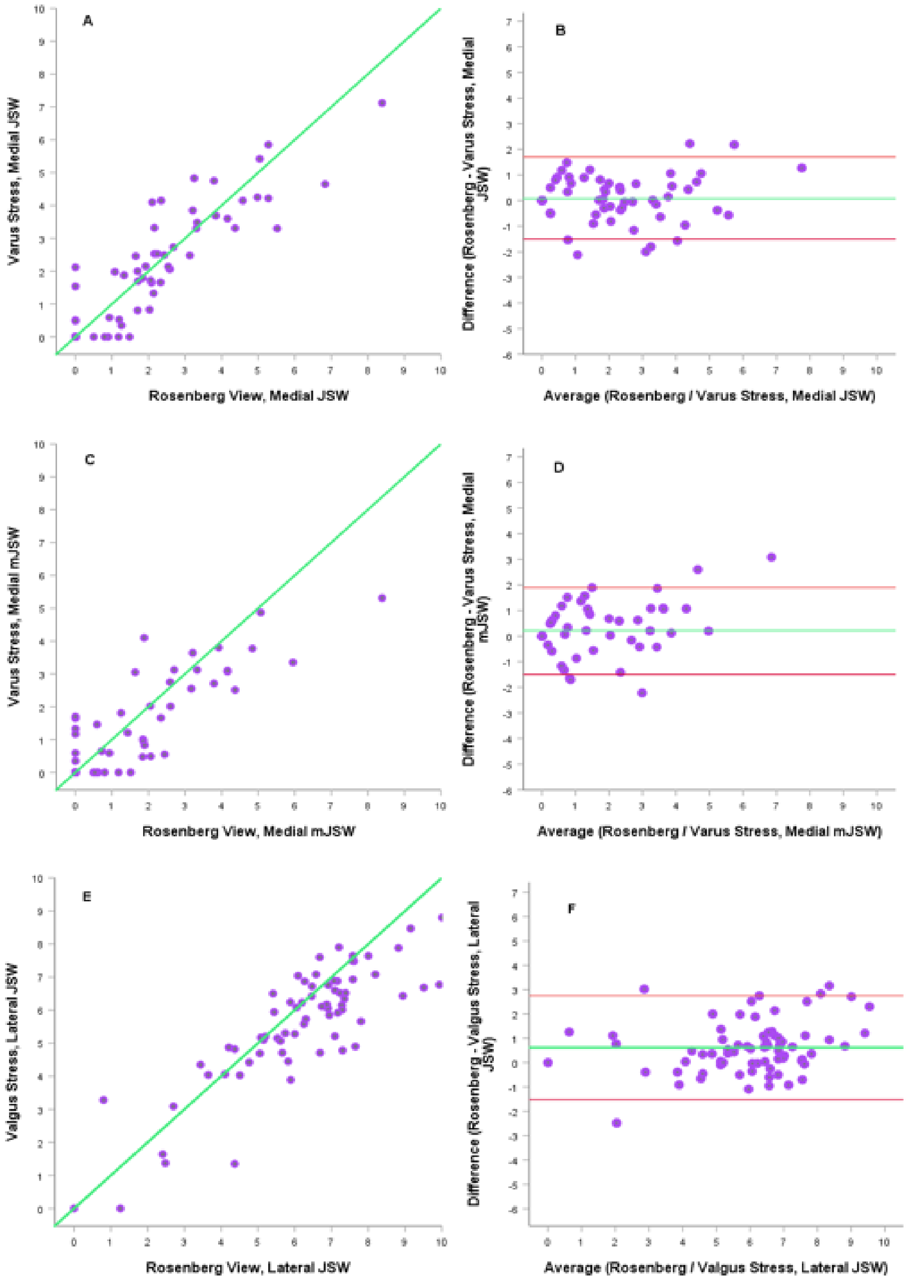

Figure 15 A/C/E: Scatter plots showing measurements between the Rosenberg view and coronal stress radiography, with the green line representing proportional linearity. B/D/F: Bland Altman plots showing differences between the two radiographic techniques, with the mean difference (green line), and limits of agreement (red lines). A+ B showing the medial JSW in varus stress, C+D showing medial mJSW in varus stress, and E+F showing the lateral mJSW in valgus stress.

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10.4 Specialized radiography vs. MRi

Medial knee compartment

In the **medial** tibiofemoral compartment, a negligible to weak correlation (JSW/mJSW; r = 0.07/0.22; CI -0.17 to 0.33/-0.06 to 0.48; p = 0.3/0.42) was shown between MRi and Rosenberg view, which were non-significant findings. Weak correlation was found medially (JSW/mJSW; r = 0.11/0.15; CI = -0.18 to 0.36/ -0.23 to 0.41; p = 0.19/0.31) between MRi and varus stress, also non-significant[2].

When looking at scatterplots in Figure 16[2], we see many are measured with zero mm JSW/mJSW radiographically, but with 1-5mm when measured JSW on MRi.

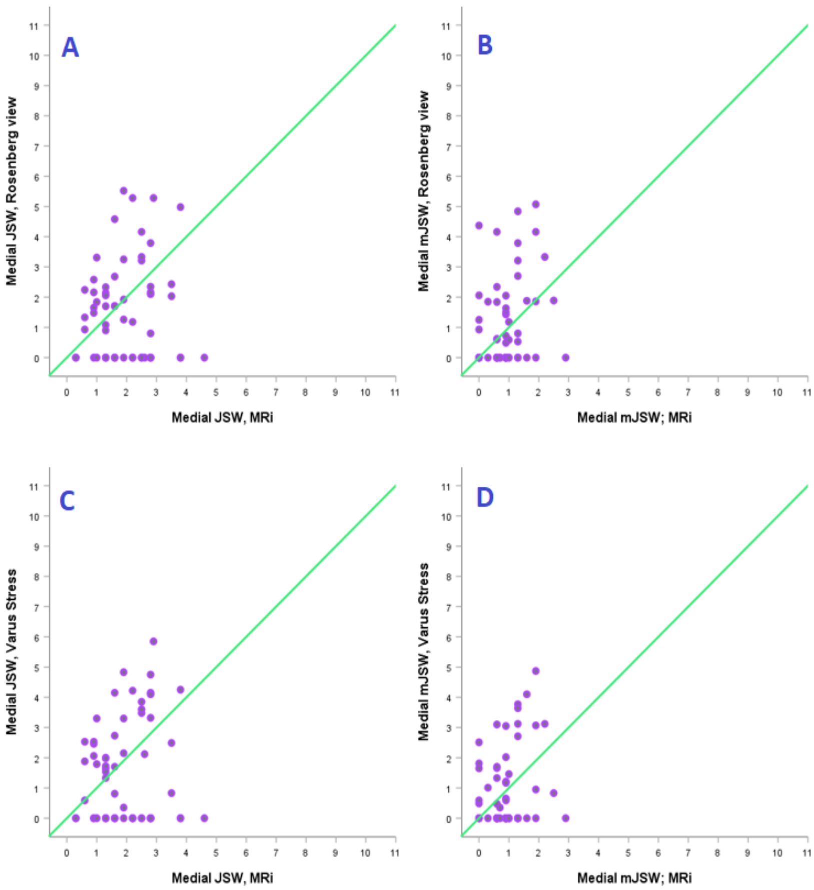

Figure 16 Medial knee compartment - Scatterplots of MRi vs. specialized radiography in measurements in A/B: JSW/mJSW of Rosenberg view vs MRi, respectively ; and in C/D: JSW/mJSW of Varus stress vs MRi, respectively.

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Lateral knee compartment

In the **lateral** tibiofemoral compartment (see Figure 17 & Figure 18[2]), a strong correlation (JSW/mJSW; r = 0.74/0.79; CI 0.58-0.85/0.67-0.87; p = 0.001) was proven between MRi and the **Rosenberg** view. A strong to very strong correlation (JSW/mJSW; r = 0.82/0.77; CI 0.68-0.90/0.62-0.87; p = 0.001) was shown between MRi and **valgus** stress.

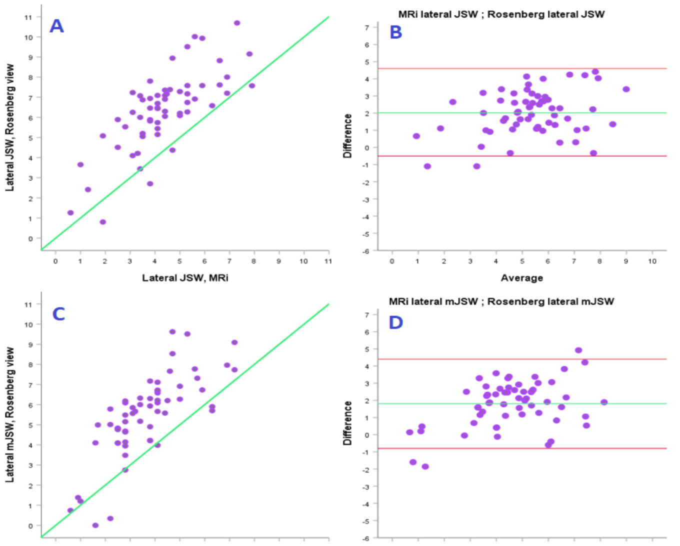

Figure 17 Lateral Knee compartment - Scatterplots (A+C) and Bland Altmann plots (B+D) comparing the Rosenberg view to MRi in measuring JSW/mJSW.

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A systematically and consistently lower JSW and mJSW is seen on MRi measurements compared to specialized radiography. This trend is visualized in the Bland Altman plots with a mean difference from 1.5-2mm, for all comparisons in the lateral compartment, accompanied by relatively wide limits of agreement, indicating lower accuracy and precision between the two techniques.

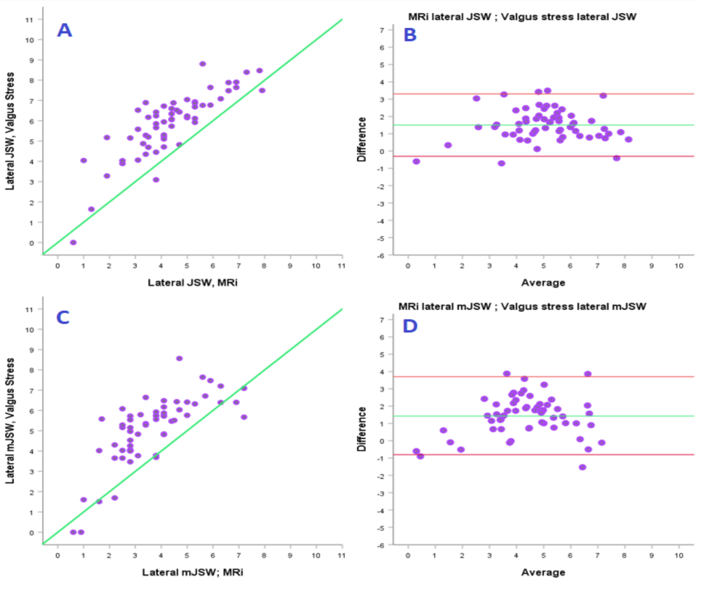

Figure 18 Lateral Knee compartment - Scatterplots (A+C) and Bland Altmann plots (B+D) comparing valgus stress to MRi in measuring JSW/mJSW.

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10.5 Incidence of overhang

As presented below in Table 6[3], a US-determined overhang of more than 1mm was seen in 72-78% and more than 2 mm in 53-56% of cases. The tibial component overhang was most seen posteromedially in both types of knee replacement, accounting for 55-59% of overhang measured over 2mm. Measurements of overhang on X-rays vs US are seen with much lower incidences in all categories, also discussed further below.

Overhang per prosthesis (%)	≥0mm	≥1mm	≥2mm	≥3mm	≥4mm	≥5mm
UKR (n=32); US	100	78.1	56.3	40.6	15.6	6.3
TKR (n=32); US	78.1	71.9	53.1	28.1	12.5	9.4
UKR (n=32); X-ray	11	9.4	4.7	0	0	0
TKR (n=32); X-ray	40.7	26.6	11	4.7	1.6	0
Incidence per location (%); US	AM	M	PM	AL	L	PL
UKR (n = 17)	29.4	11.8	58.8	-	-	-
TKR (n = 18)	0	16.7	55.6	0	11.1	16.7

Table 6

(Upper) Incidence of overhang size with Ultrasound (US) and radiographs (X-ray)

(Lower) Location of the US measured overhang above 2mm per UKR/TKR, incidence given in percentages.

Abbreviations: AM, anteromedial; M, medial; PM, posteromedial; AL, anterolateral; L, lateral; PL, posterolateral.

Sites (see Figure 10): AM=45–57.5 degrees; M=90 degrees; PM=112.5–135 degrees;

AL= 225–247.5 degrees; L=270 degrees; PL=292.5–315 degrees.

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10.6 Ultrasound vs. Conventional radiography

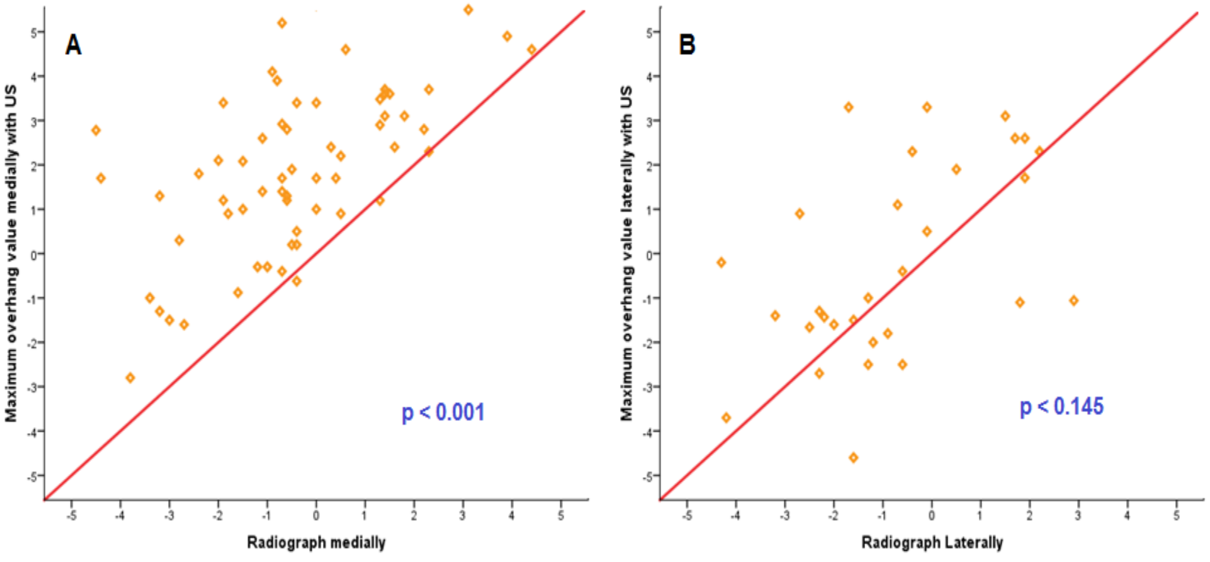

Figure 19 Scatterplots of X-rays vs. US medially (A) and laterally (B). Circles seen above the red diagonal line represent a parallax effect of X-rays, circles on the line representing equal measurements between Radiographs and Ultrasound.

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The measured medial tibial component overhang is seen in Figure 19[3], systematically underestimated by conventional X-rays. Most points are seen above or at the diagonal line, showing overhang to be underdiagnosed in 61 out of 63 patients medially. A mean difference of 2.4mm (CI 2-3; $p < 0.001$) is seen between X-rays and US on the medial side, and a mean difference of 0.5mm on the lateral side, which in turn is non-significant ($p = 0.2$). This underestimation is more subtle on the lateral side but still present when looking at the lateral tibial component overhang, showing that overhang is underestimated on X-rays in 22 out of 31 patients.

10.7 Outcomes of tibial component overhang

A positive, albeit weak correlation (r = 0,25) was found between the tibial component overhang and ΔLT, which is to some degree visualized in Figure 20[3].

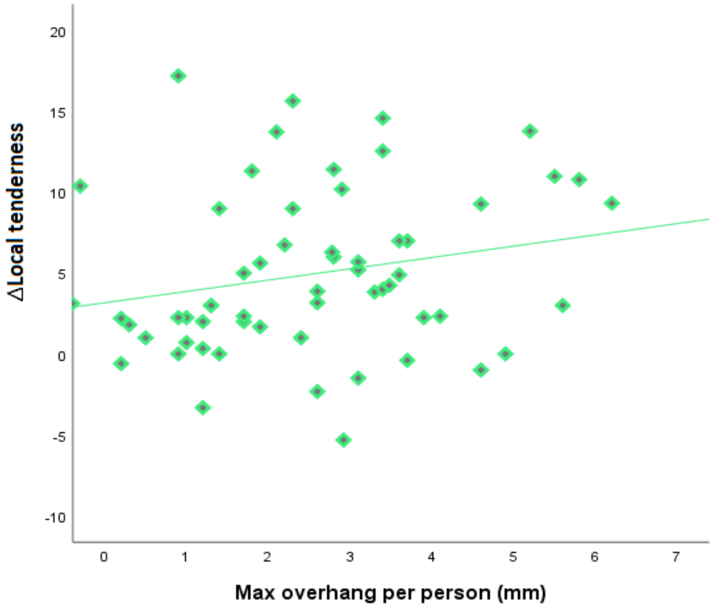

Figure 20 Scatterplot with fitted line of tibial component overhang in weak, but statistically significant correlation with ΔLocal tenderness

Subgroup analyses were performed on patients presenting **≥2mm** overhang. ΔLocal tenderness was compared first between patients with medial overhang (n = 5) and at all other locations (n=30), demonstrating a significantly higher ΔLT medially (median difference = 6.7kg/cm²; CI 2 – 11; p=0.008). Patients with medial overhang (n = 5) compared to patients with posteromedial overhang (n = 20) showed a significantly higher ΔLT medially (median difference 6.4kg/cm²; CI 2-11; p=0.04). Patients with posteromedial overhang (n = 20) compared to overhang at all other locations (n = 30) didn't prove any significant difference (p=1). Boxplots seen in Figure 21 visualize these three subgroup analyses.

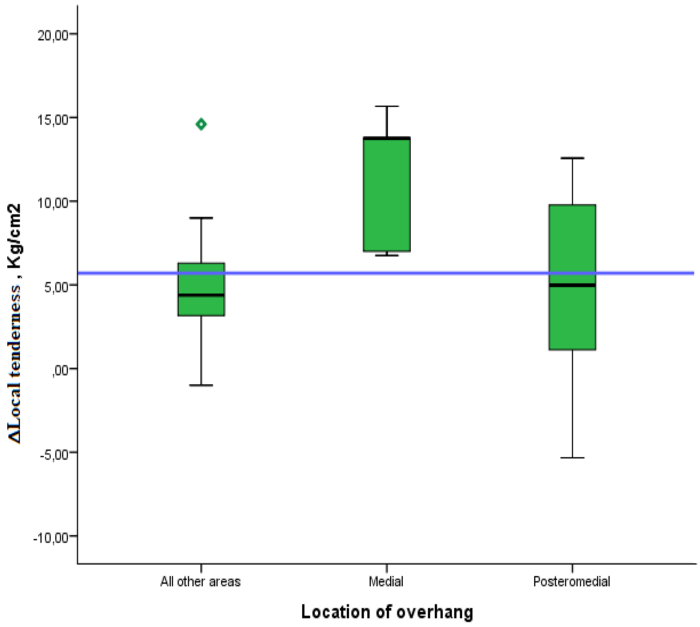

Figure 21 Boxplots visualizing subgroup analysis of patients with an overhang of ≥2mm, and their respective location. The blue line represents the median across all groups.

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11 Discussion

11.1 Reliability and agreement

Study I

When joint space width measurements of the knee are performed, the varying positioning of the knee can increase the risk of unreliable assessments. The reproducibility of two widely used techniques for measuring JSW of the knee was assessed by performing double measurements. Between each set of measurements, a two-minute break was given, and the patient was asked to move around the room. Comparing the two sets of measurements showed overall substantial reliability.

Substantial test-retest reliability (0.51- 0.74) was found of the **Rosenberg** view and **coronal** stress X-rays, indicating that these techniques' technical setup and execution are reliable. Detailed written instructions were used by the radiographer, and any risk of variation introduced by different radiographers is plausibly not significant. Koppens et al. [54] found similar reliability results for standardized **valgus** stress X-rays when measuring JSW medially and laterally. In another study using the same standardized coronal stress device, coronal laxity following TKR was measured, where Kappel et al. [55] found excellent reliability for angular measurements. When using a standardized device and protocol, it is fair to claim that the test-retest reliability of stress X-rays is high.

Other studies investigating the test-retest reliability of the **Rosenberg** view were not found in the literature.

Furthermore, observers must be in an acceptable range of agreement. This agreement was investigated by comparing the observers' inter- and intrarater measurements.
Here, we found substantial to almost perfect intra- and interrater agreement for the **Rosenberg** view and **varus** stress measurements in the **medial** compartment. This indicates that raters measure similarly with these techniques and can correctly determine the presence of bone-on-bone since unfavorable results have been reported for cases with partial-thickness cartilage loss [56].

We found moderate to substantial intra- and interrater agreement in the lateral compartment for the **Rosenberg** view and **valgus** stress. These results in the **lateral** compartment are similar to the study mentioned above from Koppens et al. [54]. Our study shows a slightly better agreement when using JSW to measure cartilage height instead of the more subjective mJSW. This could be explained by standardized methods of measuring cartilage height in areas with incongruent joint surfaces being the better choice instead of subjective minimal cartilage height measurements[57].

To help rule out uncorrectable **varus** deformities, it is also important to ensure a sufficient medial opening during valgus stress[12]. This study has shown a better substantial agreement of **medial** JSW than mJSW during **valgus** stress, indicating a better measurement for medial opening. Koppens et al. showed similar results, supporting these findings [54]. Although proving good reliability and agreement, **valgus** stress has previously been concluded to be overstated when assessing suitability for a mUKR, as the varus deformity cannot be adequately determined until after osteophyte removal [58].

Study II

Moderate to substantial agreement on MRi measurements were found between all three raters. Agreement in the medial mJSW between rater 1 and 3 was only fair, and overall agreement was considered acceptable in this study. A previous study showed good inter- and intrarater agreement when assessing the knee's cartilage status [59], supporting our overall findings. Test-retest analysis was deemed unnecessary in this study, as previous studies have shown high reliability of knee pathology measurements on MRi, also considering varying field strengths [60].

50% of the population in this study consisted of patients offered mUKR, with close to full-thickness lateral compartment cartilage, which resembles normal cartilage anatomy or early OA changes. Bone-on-bone in the medial compartment was seen in a larger portion of the study population, and these measurements showed lower agreement between raters.

Better agreement is seen in the lateral compartment, where most participants had normal cartilage compared to the medial compartment, where most participants had severe OA. Another explanation of the lower agreement in the medial compartment could be the lower field strength and resolution achieved with extremity MRi, making it difficult to measure such small distances accurately.

Study III

US is not considered the gold standard for analyzing metal components in contrast to bone dimensions. Still, our study has shown good reliability when using this method with modest US technology. With a standard US-probe, the tibial bone surface and the metal component's edge are quickly found, allowing for instant and precise overhang measurement.

The increasing popularity of visualizing bone surfaces and structures with US usage is interesting, as more advanced techniques, including orthopedic implant visualization, are becoming available [61]. This helps prove how low-cost, easy-to-use, portable equipment can be used to assess tibial component overhang quickly and precisely.

11.2 Comparisons of techniques

Study I - Rosenberg vs. Coronal stress

A strong to very strong correlation was found of cartilage height measurements between the Rosenberg view and each stress technique in the relevant knee compartment. Acceptable limits of agreement were observed **medially** for JSW/mJSW, with minor systematic errors and a mean difference close to zero (see Figure 15B+D). These results indicate similar precision and accuracy between techniques for medial measurements.

The difference between mJSW and JSW **medially**, when observing bone-on-bone, was discovered more often when using mJSW instead of JSW. Bone-on-bone was found in 30/73 patients (mJSW) and in 22/73 (JSW). This finding is also relevant, as determining bone-on-bone presence is necessary for determining suitability for mUKR [12, 25], as less favorable outcomes have been reported in cases where there was only partial-thickness cartilage loss [56].

Less acceptable limits of agreement (-1.5mm to 2.8mm) were observed **laterally** for JSW, with a mean difference of 0.62mm (see Figure 15F). These findings indicate a relatively high accuracy but low precision between techniques in lateral compartment cartilage height measurements. When assessing full-thickness cartilage in the **lateral** compartment, the presence of full-thickness cartilage is necessary upon considering a mUKR [12], and it is unknown whether a 0.62mm difference between these methods is clinically relevant. Although, it isn't likely that this difference of 0.62mm would profoundly influence a decision between offering a mUKR or TKR. Our findings are consistent with the literature, where the Rosenberg view is argued to determine the **lateral** cartilage thickness sufficiently [56], especially posterolaterally. The lateral femoral condyle's contact point with the tibial plateau moves posteriorly during flexion [50, 54], tending to show wear posteriorly located. Our findings suggest that the Rosenberg view can similarly determine lateral cartilage height to valgus stress, but bearing in mind, this would be measured 0.45 mm thicker.

There are some **advantages** and **disadvantages** to both methods.
Various stress X-ray techniques have been used, as seen in the literature[62-66]. Still, the Telos **stress** device has the **advantage** of offering a reliable and standardized pressure application approach, which eliminates investigator radiation exposure, and resources spent performing the technique. Another advantage of stress X-rays could be providing case-by-case information on the correctability of knee deformity, ligament balancing, and joint stability. Still, a previous study assessed this to be sufficiently determined clinically or intraoperatively [58].
The **disadvantages** of coronal **stress** X-rays and a pressure device are the unit costs, the need for technique savvy and trained radiographers, time consumption of the device setup twice for varus and valgus, and the extra radiation exposure due to multiple X-rays. There is a minor discomfort involved in the coronal stress, but this was considered very moderate.
The **Rosenberg view's advantages** are that it does not need extra specialized equipment or staff, the setup is relatively quick and simple, and the technique is already widely used in the work-up for mUKR[56]. Earlier studies have also proven a higher specificity and sensitivity compared to conventional anteroposterior X-rays [27]. This could suggest that the additional cost and radiation of a conventional X-ray, along with the two additional coronal stress X-rays, could be spared. In the work-up for a mUKR, lateral projections and Skyline X-rays are necessary [12], only increasing the number of radiographs performed. Therefore choosing only the Rosenberg view could minimize the total cost and number of X-rays per patient undergoing knee replacement surgery.

Study I suggests that articular cartilage height is determined similarly with both the Rosenberg view and coronal stress X-rays and is sufficient in determining suitability for mUKR, if correctability and ligament stability are clinically normal. When radiographic and clinical findings are conflicting, additional imaging may still be indicated, especially when presented in the lateral knee compartment.

Study II - MRi vs. specialized radiography

In the **medial** knee compartment, no significant correlation was found between MRi and specialized X-ray measurements. Bone-on-bone was seen in several patients in the medial compartment with specialized X-rays but measured several millimeters of JSW/mJSW on MRi measurements (Figure 16). These results are the opposite of what would be expected. Any overestimation of the JSW/mJSW would theoretically happen with X-rays because of its two-dimensional imaging of a three-dimensional structure and X-ray measurements being prone to error due to the positioning of the knee joint [67-69].

Our results are supported by earlier findings in the literature, in which MRi measurements correlate poorly with mJSW measurements on knee X-rays [70-72]. This study adds to existing knowledge that these specific specialized X-ray techniques pose the same measurement mismatch when compared to MRi. These mismatches could be explained by knee joint positioning and the lack of weight-bearing MRi, but earlier studies have shown this to be of minimal difference[44].

These mismatches are the clinical reality when using MRi compared to specialized X-rays and present a significant concern of MRi's ability as a general screening tool for determining cartilage height in end-stage OA knee compartments, especially when using an extremity MRi. Furthermore, bone-on-bone can be assessed sufficiently with a cheap and straightforward X-ray image with the Rosenberg view or varus stress [1] and should therefore not be used for this purpose.

In the **lateral** compartment, a strong to very strong correlation was found between MRi and specialized X-rays. Scatterplots and Bland Altman plots showed that MRi consistently measured the cartilage height 1.5-2mm smaller. These results are consistent with the literature, with a better correlation between X-rays and MRi in knee compartments without end-stage OA, when considering that participants in this study generally had more intact cartilage in the lateral compartment. Full-thickness cartilage should be present when offering a mUKR[12, 56] and will ultimately be inspected when the knee is opened during surgery[73]. With the relatively small difference in measurements between specialized X-rays and MRi, while considering their correlation, we can conclude that both types of specialized X-rays and MRi can be used to confirm full-thickness cartilage in the lateral compartment. MRi for general screening of cartilage height assessment and patient suitability for mUKR should be discouraged since a single X-ray can help reach the same conclusion.

Study III - Radiography vs. Ultrasound

We have proven that ultrasound is a relevant tool to investigate the presence of overhang, especially medially/posteromedially. Compared to X-rays, a significant difference was found between techniques when looking medially, but not laterally. This could indicate that radiographs are enough to confirm/exclude overhang laterally with X-rays. Still, this finding could be due to the small sample size since only half of the participants received a TKR. The main point of using ultrasound is to avoid the two-dimensional parallax effect of X-rays. Optimally, postoperative X-rays should be performed with fluoroscopy guidance [74, 75] or oblique X-rays, but these are not always possible and also cause more radiation.

Other techniques such as metal artifact reduction CT/MRi provide a solution to this problem but are costly, time-consuming, not always available, and can cause excess radiation (CT). This should encourage US use, especially when such a device often is available in the outpatient department and can help avoid the cost, time, and radiation of having additional X-rays performed.

11.3 Outcomes and incidences

Pressure Pain Threshold

A positive but poor correlation was found in Study III between the overhang and patients' local pain level. Subgroup analysis results showed that medial overhang was associated with a higher ΔLT. This is similar to previous findings, where worse outcomes are seen when a medial overhang is present[76]. The anatomical locations of the medial compared to the lateral collateral ligament could help explain these findings medially as the medial ligament runs closer to the knee replacement's edge. The maximal overhang per patient was most frequently found posteromedially (see Table 6), but this location was not associated with a higher ΔLT. The anatomical location and movement of the MCL could again explain these results, possibly not being irritated by the posteromedial overhang under knee flexion and extension. A previous study supports our results, in which they argued that MCL loading increases above 2mm of tibial component overhang medially, which in turn could lead to pain [40].

Prevalence, incidence, and size of overhang

This Study presents a new technique that measures the true tibial component overhang in real-time, which could help avoid the literature's inconsistencies regarding prevalence, incidence, and sizes of overhang. Studies have classified overhang as being "minor" (<3mm), "major" (>3mm) [77, 78], or excessive (>2mm) [79], which is inconsistent and could lead to differences in the reporting of incidences.

The technique used to measure overhang also varies in the literature, possibly adding to the inconsistency. One Study measured overhang on TKR's dichotomously (>/< 1mm), showing a medial overhang incidence of 18.0% and lateral overhang in 32.2% of patients [76]. Another study's incidence of TKR's showed 60% (<3mm), while 9% (>3mm) [78]. In a study of mUKR, an incidence of 10% (>2mm) was found [79]. In our study, at a high-volume knee replacement unit, an incidence of 53-56% (>2mm), 28-40% (>3mm), and 12-15% (>4mm) were found with US, indicating that tibial component overhang is generally underreported. Naturally, individual surgeon thoroughness and implant brand could also influence the prevalence.

11.4 Methodological considerations and limitations

Study I + II

These two studies required ample time and focus since the measurement processes lasted many consecutive hours at a time, possibly resulting in observer fatigue. Raters might also modify an aspect of their measurement behavior when they know they are being observed, better known as the Hawthorne effect [80].

Diagnostic screens were not used for the X-ray analysis, which decreases the quality of imaging observed, but were not deemed necessary for this study I. Most data received in these studies were zero-limited and presented a floor effect, making the choice of statistical analysis very difficult. After many statistical discussions amongst the research group and guided by statisticians at the University of Copenhagen, it was decided that agreement and reliability data was converted from numeric to ordinal data in order to use a weighted Cohen's kappa.

Alignment and correctability of the knees with coronal stress radiography have not been included in these studies. Still, they could help investigate other aspects of the especially coronal stress X-rays in the work-up for mUKR. The positioning angle of the knee in each technique was different, theoretically measuring different cartilage heights sites, but this also represents the clinical limitations in daily practice.

Extremity MRi, including a lower field strength (1,5 T), larger pixel size, and lower resolution, was used instead of a high field strength and high-resolution MRi. This was done to investigate the usefulness of this cheaper and faster MRi technique in assessing the OA distribution of the knee. Only two-dimensional measurements of the cartilage height were performed, as it was not feasible to assess a three-dimensional cartilage volume, which could be more informative. The cartilage height measurements were performed from cortex to cortex but could optimally have been measured on each surface to avoid measuring structures other than cartilage. Weightbearing MRi measurements would also be optimal when comparing to weight-bearing/stress radiographs. Although, the clinical reality is that weighted MRi of the knee is rarely available.

MRi also gives other information such as ligament and meniscus status and subchondral edema, which wasn’t included in study II.

Comparing costs and time spent for each technique could also have given more nuance to comparing their advantages and disadvantages, but it was not within the scope of these studies.

Study III

This study was performed at three months follow up with measurement of pressure pain threshold, which is relatively early regarding postoperative knee swelling and pain. Still, it could be argued to be an important timing of assessing a particular tenderness per patient. This was especially reflected in the statistically significant differences in tenderness at sites with overhang compared to sites without. Optimally, patients would also have been followed up at one year, but this was not feasible due to time constraints. The sample size calculated was based on the presence of an overhang, making measurements laterally underpowered since only half of the patients received a TKR.

Due to the lack of a standardized steel ball for calibration was done with fixed points on the knee replacements. This could have produced a margin of error on mUKR measurements, which the research group accepted.

Optimally, the total area of overhang in each region could have given more accurate information on the incidence and outcome of overhang.

The lack of overhang measurements of the femoral component could pose a limitation, as this may also cause tenderness. The presence of osteophytes could cause the knee pain measured, but this was not considered. Since soft tissues medially and laterally were of particular interest, anterior and posterior measurements were not included.

12 Conclusions

Study I

In Study I, the specialized X-ray techniques investigated were found to have high reliability and agreement in a representative prospective cohort. The strong correlation between the Rosenberg view and coronal stress X-rays suggests that these techniques are valid can replace each other assessing mUKR eligibility. The Rosenberg view could help save costs and extra radiation compared to standardized stress X-rays, although each technique has advantages and disadvantages.

Study II

In Study II, our results showed only fair to substantial interrater agreement on MRi. A non-significant weak correlation of MRi to X-ray cartilage height measurements was shown in the medial compartment and a significantly strong correlation in the lateral compartment. These results suggest that extremity MRi should not replace the specialized X-ray techniques investigated in these studies, primarily regarding articular cartilage height assessment. MRi should only be used in atypical case presentations, knowing that extremity MRi is of a lesser quality than MRi with a higher field strength and resolution.

Study III

In Study III, we found that X-ray has its limits post-operatively, risking a parallax effect and underestimation of a possible presence of tibial component overhang, which in turn can be a cause of local tenderness, especially medially. Results prove ultrasound to be a reliable method of investigating tibial component overhang and is relatively easy to learn. This should encourage orthopedic surgeons to use this extra tool in the outpatient department when X-ray images cannot explain a patient’s soft tissue complaints.

13 Perspectives and future research

Healthcare systems' cost-effectiveness will continue to be important down to each patient and each diagnostic test performed, making it essential to choose each test correctly. It is important to ensure that each patient receives the highest level of care without performing unnecessary imaging, resulting in increased costs and radiation. The Rosenberg view has proved to have the ability to replace coronal stress X-rays in assessing the cartilage height. Further studies concerning alignment, ligament balancing, and varus knees' correctability are necessary to fully judge the coronal stress radiographic technique with the Telos apparatus. In time, it would also be interesting to investigate if using the Rosenberg view or coronal stress X-rays could help lower either risk of revision and risk of conversion from mUKR to TKR.

Further studies are needed to compare X-ray measured joint space and alignment with other measurable variables on MRi, such as subchondral edema, cartilage lesion severity, along with medial/lateral collateral ligament and meniscus status. Both quality and cost-wise, using an extremity MRi to assess eligibility for mUKR could prove to be very costly while also providing some doubtful information regarding cartilage height. Quality-wise, this could be avoided by high-tesla MRi scans with higher imaging quality. Still, these higher-quality MRi scans also are even more expensive and time-consuming, which could lead to very high costs if used to screen for mUKR eligibility. Though, we might see technological advances that will increase the quality and decrease the costs of MRi.

Ultrasound has proved to be an easy and cheap diagnostic test to perform in an outpatient department setting. Since the incidences found in this study are much higher than the generally reported incidences, it could be postulated that a significant amount of overhang is underreported due to the parallax effect of X-rays.

Other diagnostic imaging modalities, such as metal artifact reduction CT/MRi, could prove to be even better at assessing the total area of overhang and the component placement/orientation. This could provide valuable information regarding the presence and effect of tibial component overhang in future studies.

14 Postscript

It always seems impossible until it is done.

-Nelson Mandela

15 References

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16 Appendix of published papers

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KNEE ARTHROPLASTY

The Rosenberg view and coronal stress radiographs give similar measurements of articular cartilage height in knees with osteoarthritis

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Abstract

Purpose Choosing the optimal radiographic methods to diagnose the cartilage height and degree of knee osteoarthritis is crucial to determine suitability for unicompartmental knee replacement. This study aims to evaluate and compare articular cartilage thickness measured using the Rosenberg view and coronal stress radiography. Intra- and interrater agreement and test–retest reliability of each method were determined. The hypothesis of the study was that the Rosenberg view and coronal stress radiographs provide similar assessments of articular cartilage height in the medial and lateral knee compartments of osteoarthritic knees.

Methods A prospective diagnostic study, including 73 patients was performed. Inclusion criteria were enrollment for either a medial unicompartmental or a total knee replacement. Radiographs were taken as the Rosenberg view, and coronal stress radiography using the Telos stress device. Repeated measurements were performed. Experienced knee surgeons performed measurements of cartilage height at a standardized location of joint space width (JSW), and a rater-perceived location of minimal joint space width (mJSW), thus allowing for reliability and agreement analysesusing weighted kappa. Coronal stress measurements were ultimately compared to the Rosenberg view using Spearman's rank correlation.

Results A total of 12,264 measurements were performed. The radiographic methods proved substantial reliability. Intra- and interrater agreement showed substantial to almost perfect agreement. A very strong correlation was observed in the medial knee compartment ($r=0.91$; $CI=0.84–0.95$; $p<0.001$), with a mean difference of 0.1 mm and limits of agreement of −1.5 to 1.7 mm, when comparing JSW between the Rosenberg view and varus stress. Only a strong correlation was observed medially when using mJSW, and when using this measurementmore incidences of bone-on-bone were observed than when measuring with JSW. A Strong correlation was observed in the lateral knee compartment ($r=0.83$; $CI=0.71–0.89$; $p<0.001$), with a mean difference of 0.62 mm and limits of agreement of −1.5 to 2.7 mm, when comparing JSW between the Rosenberg view and valgus stress.

Conclusion The Rosenberg view is similar to 20° coronal valgus–varus stress radiography for determining articular cartilage thickness. Both techniques can be used in a clinical setting. Therefore, extra radiographs, equipment and expertise could be saved, when solely utilizing the Rosenberg view which is simple to perform.

Level of evidence III.

Keywords Rosenberg · Valgus · Varus · Stress radiography · Telos · Medial unicompartmental knee replacement (UKR) · Arthroplasty · Total knee arthroplasty (TKR)

Introduction

Radiography is the gold standard for diagnosing osteoarthritis (OA) [1], as it is a quick, relatively safe and easy technique to assess the articular cartilage thickness [2–4]. Conventional radiography of the knee, apart from the lateral view, consists of a weight-bearing anteroposterior radiograph, with the knee in its natural anatomical position [5,

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6]. The Rosenberg view (45° flexion posteroanterior projection) is known to be more sensitive and specific than anteroposterior conventional radiography, in determining joint space narrowing in patients with osteoarthritis [7]. Aside from conventional radiography, the Rosenberg view [7] and coronal plane stress radiography are recommended in various radiographic algorithms when considering partial knee replacement [1, 8, 9].

It is still widely debated whether a total knee replacement (TKR) or a medial unicompartmental (mUKR) is better. Some studies have found advantages to mUKR such as a better range of motion, knee dynamics, quicker rehabilitation, higher quality of life, and fewer complications [10, 11], and adhering to the correct indications for mUKR are essential to achieve optimal results [8, 12].

It is essential to know the level of degenerative disease in the remaining compartments when considering a unicompartmental knee replacement. Therefore, it has been suggested to add coronal stress radiography in the diagnostic process to confirm bone-on-bone in the medial compartment, full-thickness cartilage in the lateral compartment, and a correctable varus deformity [8]. To ensure the right implant for the right patient, it is essential to know how different types of radiography discriminate between levels of degenerative disease in the different compartments.

However, only limited information is available regarding inter- and intrarater agreement for coronal plane stress radiography and the Rosenberg view. Studies directly comparing the Rosenberg view with coronal stress radiography in patients with knee osteoarthritis are scarce yet choosing the better radiographic methods to diagnose knee osteoarthritis could save both radiation and cost in the diagnostic process.

This study aims: (1) to analyze the test–retest reliability of the Rosenberg view and coronal plane stress radiography using a commercially available stress device in a cohort of patients with knee osteoarthritis, (2) to assess the inter- and intrarater agreement for these methods, and (3) to investigate if the Rosenberg view can determine articular cartilage thickness similar to coronal stress radiography.

The hypothesis of this study was that similar measurements are achieved using the Rosenberg view and coronal stress radiographs measurements of cartilage height in knees with osteoarthritis.

Material and methods

This study is a Level III diagnostic study. Guidelines for reporting reliability and agreement studies (GRRAS) [13] and technical procedures stated in the Standards for reporting diagnostic accuracy studies (STARD) [14] were followed. One hundred and sixty patients were invited to participate in this study at a high-volume knee arthroplasty unit. Seventy-three patients were prospectively included from August 2018 to June 2019. Eighty-seven declined participation. A patient flowchart can be seen in Fig. 1. The inclusion criterion was participants planned for either a TKR or a mUKR at the time of enrolment. Participants were included by forming a convenience series, depending on the radiographic ward's capacity before the individual date of surgery. Exclusion criteria were pregnancy, severe systemic disease, employment at the department, or lack of ability to comply with simple instructions. Forty-four patients were listed for a TKR, and twenty-nine were listed for a mUKR. Preoperative knee alignment was not assessed as a criterion for inclusion/exclusion, as participants enrolled for both mUKR and TKR were included, and the discrepancy between these two groups is of interest. Patients were not assessed as to having either primary or secondary osteoarthritis.

One experienced radiographer performed all radiographic examinations, using a Siemens Axiom Luminos dRF with fluoroscopy (Siemens Healthcare GmbH, Erlangen, Germany). The focus was set to Fine, with an opening of 0.6 mm. A sequence of radiographs was performed for each patient, starting with the Rosenberg view, followed by coronal plane stress radiographs. Patients were asked to walk around the room for 2 min, followed by radiographs being performed again in reverse order.

Rosenberg view

Patients were positioned standing with bare flat feet with full weight-bearing evenly divided on both feet. Both knees were equally flexed to 45°. The patella was as close as to the detector as possible without touching it. A posteroanterior X-ray beam with a 10-degree caudal inclination was used (see Fig. 2A [15]). For calibration, a 25 mm steel ball was placed either medially or laterally on the femoral condyle at the same anteroposterior level as the middle of the joint space [7]. Criteria of approval for the radiographer were that the joint space was projected free and the patella was projected centrally between the femoral condyles.

Coronal stress

Patients were positioned supine with the knee flexed to 20–30° with a supportive triangular pillow to relax the knee's muscles and the posterior capsule [2]. A specifically manufactured stress device from Telos (Telos GmbH, Hungen–Obbornhofen, Deutschland) was used. The Telos stress device (Fig. 2B and Fig. 2C) was placed first in either valgus or varus stress and hereafter switched. The middle pressure device was placed precisely in the middle of the two counter supports, at the joint space either laterally for valgus or medially for varus. A maximum of 130–150 N (15kp) of pressure was applied. The central anteroposterior beam was

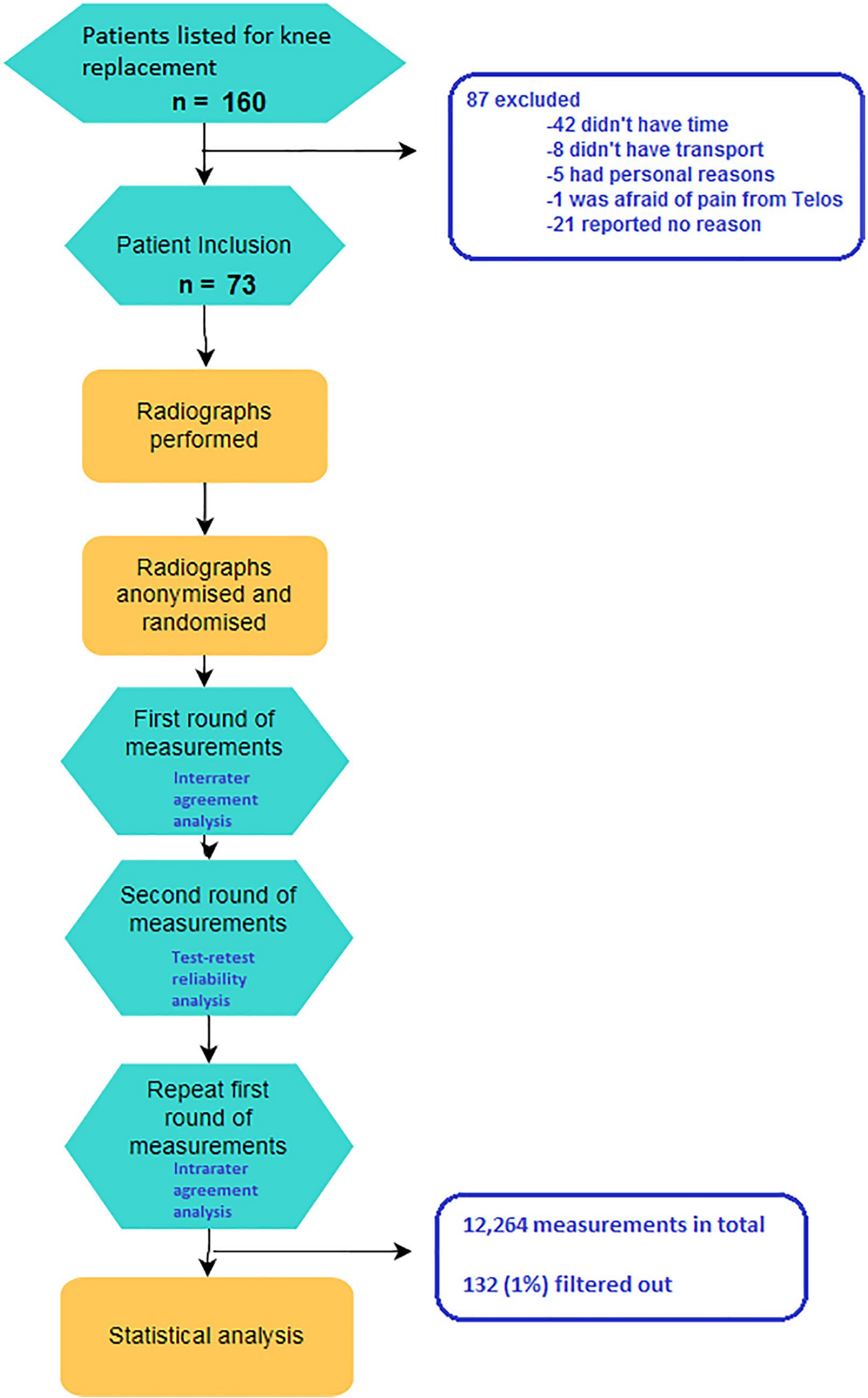


Fig. 1 Flowchart

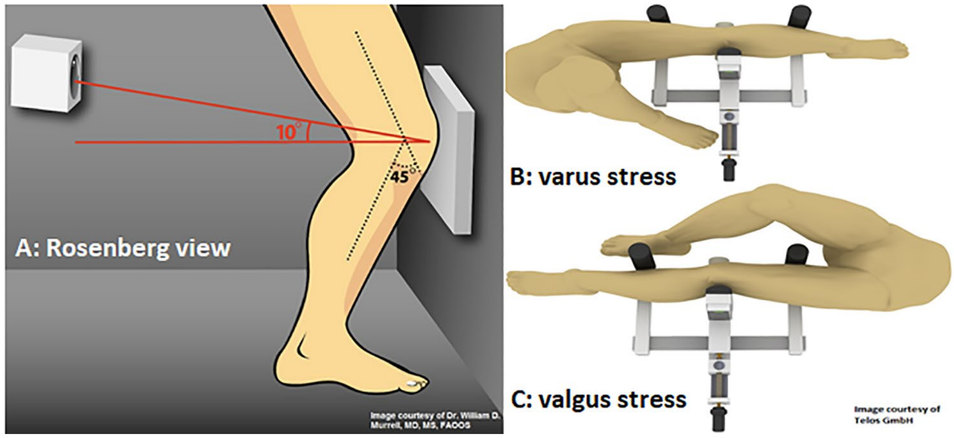


Fig. 2 Method of Rosenberg a, Telos varus stress b, and valgus stress radiography c

pointed 5 degrees caudally approximately 1 cm under the patella. For calibration, a 25 mm steel ball was placed at the same anteroposterior level as the middle of the joint space either medially or laterally. Criteria of approval for the radiographer were the same as for the Rosenberg examination.

Measurements

Radiographs were uploaded to a PACS digital system, which allowed calibration via the Impax-Orthopedic-Tools program (Agfa-Gevaert, Mortsel, Belgium). Radiographs were anonymized using Syngo.via Client software (Siemens Healthcare GmbH, Erlangen, Germany), and each participant received a blinded identification number. Raters were unaware of information such as health, sex, age, or medical history.

Three experienced knee surgeons (rater 1, 2, and 3) used K-PACS workstation Version 1.0.1 (Image Information Systems Europe GmbH, Rostock, Germany) with magnification calibrated, anonymized, and randomly ordered radiographs in DICOM-files. Joint space width (JSW) and minimal joint space width (mJSW) were measured in millimeters, with one decimal, in the knee's medial and lateral compartments. JSW was measured at the middle point of each femoral condyle perpendicularly to the tibial plateau. If the projection angle did not seem to sufficiently clear the joint space, the tibial plateau's anterior rim was used as a reference [16] (see Fig. 3). mJSW was measured where the surgeon believed the joint space width to be the smallest on weight-bearing surfaces.

Alignment was measured anatomically on pre-operative conventional radiographs [17], which were used by each surgeon to assess the indications for surgery.

Regular computer screens were used for measurements. The software allowed for zoom for more accurate measurements. The three raters independently measured all radiographs in three rounds, with a minimum of 2 weeks between each round. The first round consisted of the first radiographic sequence taken to allow for interrater analysis. The second round of measurements consisted of the second radiograph sequence taken to allow for the test–retest assessment of the radiographic setup and technique. The third round consisted of repeated measurement of the first radiographic sequence taken to allow for intrarater analysis. All measurements were analyzed for erroneous data such as typing errors or side confusion, in which case data were deleted.

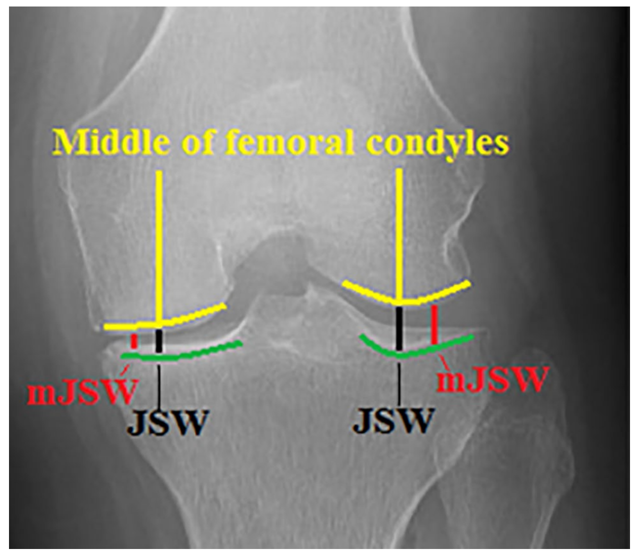


Fig. 3 Radiographic measurement technique of JSW and mJSW of both Rosenberg and varus/valgus stress views

Statistics

The inclusion of 50 subjects is sufficient for reliability and agreement studies like this, and an adequate level of power can be achieved by increasing the number of raters from two to three, instead of increasing the number of participants [18, 19]. The sample size was increased by 50% to secure a buffer.

JSW and mJSW data were rounded to nearest integer in mm. Since, the data were right-skewed and clustered towards zero we used non-parametric weighted Cohen's Kappa for reliability and and inter/-intrarater agreement assessments [20, 21]. Strength of reliability and agreement was categorized by their weighted kappa statistic as follows; poor (<0.00); slight (0.00–0.20); fair (0.21–0.40); moderate (0.41–0.60); substantial (0.61–0.80); almost perfect (0.81–1.00)[22]. Data used to compare radiographic techniques consisted of the medians of all raters' measurements in round 1, for each measurement type. Spearman's rank correlation coefficient was used to summarize the strength of relationship between the radiographic techniques [23]. The strength was interpreted as follows; negligible (0–0.1); weak (0.1–0.39); moderate (0.4–0.69); strong (0.7–0.89); very strong (0.9–1). Bland–Altman and scatterplots with mean differences showing accuracy, and limits of agreement showing precision, were made to show the strength of agreement between techniques [24]. Demographic data was compared using the Student's t-test, and the paired t-test. SPSS statistical package version 22 (IBM SPSS Inc, Chicago, IL) and Microsoft Excel (Microsoft Corporation, Washington, USA) with Realstatistics-data-analysis-tool add-in were used to calculate linear weighted kappa with 95% confidence interval. Strength of reliability and agreement was categorized by their weighted kappa statistic as follows; poor (<0.00); slight (0.00–0.20); fair (0.21–0.40); moderate (0.41–0.60); substantial (0.61–0.80); almost perfect (0.81–1.00) [22]. Data used to compare radiographic techniques consisted of the medians of all raters' measurements in round 1, for each measurement type. Spearman's rank correlation coefficient was used to summarize the strength of relationship between the radiographic techniques [23]. The strength was interpreted as follows; negligible (0–0.1); weak (0.1–0.39); moderate (0.4–0.69); strong (0.7–0.89); very strong (0.9–1). Bland–Altman plots showing mean difference and limits of agreement, along with scatterplots, were calculated to show the strength of agreement between variables [24]. Demographic data were compared using the Student's *t* test, and the paired *t* test was used for comparison of means between techniques.

Ethics

This study has obtained approval from the Danish Ethics Committee (Approval-id H-18010291), and participants gave informed consent prior to inclusion.

Results

The mean age of patients was 73 (8.1) ears, with no difference between sexes (p = 0.23) and implant types ($p = 0.26$). The mean BMI was 28.1 (4.6) kg/m+, with no difference between sexes ($p = 0.45$) or implant types ($p = 0.88$). The mean pre-operative alignment for mUKR knees was 3.5(3.7) in varus and 0.1(7)° for TKR knees. All raters and participants completed the protocol. A total of 12,264 measurements were performed, with 132 erroneous measurements/registrations filtered out, consisting of 1% of the dataset. Test–retest reliability and intra- and interrater agreement results are discussed below and presented in Table 1, with weighted Cohen's kappa coefficients and a 95% confidence interval. One patient's valgus stress radiographs were eliminated from the analysis due to the first valgus radiograph's poor quality.

Rosenberg view

Mean measurements of JSW(SD)/mJSW (SD) were 1.8(1.9)/1.3(1.8) mm in the medial compartment, and 6.3(2.1)/5.3(2.1) mm in the lateral compartment. Test–retest proved substantial reliability in both medial (JSW/mJSW; weighted Kappa = 0.71/0.74) and lateral compartments (JSW/mJSW; 0.66/0.63). Intrarater analysis for the Rosenberg view showed substantial to almost perfect agreement medially (JSW/mJSW; 0.78–0.89/0.85–0.92) and moderate to substantial agreement laterally (JSW/mJSW; 0.74–0.80/0.59–0.77). The interrater analysis showed approximately the same for the medial (JSW/mJSW; 0.73–0.77/0.77–0.83) and lateral (JSW/mJSW; 0.63–0.68/0.42–0.60) joint space, as the intrarater analysis did. The lateral mJSW was the only category that showed only moderate agreement for the interrater analysis.

Varus stress

Mean measurements of JSW(SD)/mJSW (SD) were 1.7(1.8)/1.1(1.4) mm in the medial compartment, and 7.5(1.5)/6.6(1.4) mm in the lateral compartment. Test–retest showed substantial reliability medially (JSW/mJSW; 0.71/0.73) and moderate reliability laterally (JSW/mJSW; 0.54/0.45).

Intrarater analysis for varus stress radiography showed substantial to almost perfect agreement medially (JSW/mJSW; 0.75–0.81/0.78–0.86), and moderate to substantial agreement laterally (JSW/mJSW; 0.66–0.77/0.47–0.62). The interrater analysis showed substantial agreement medially (JSW/mJSW; 0.68–0.79/0.73–0.79), but only fair to moderate agreement laterally (JSW/mJSW; 0.32–0.52/ 0.26–0.43).

Valgus stress

Mean measurements of JSW(SD)/mJSW(SD) were 6(1.7)/5.5(1.6) mm in the medial compartment, and 5.6(1.8)/4.9(1.8)mm in the lateral compartment. Test–retest analysis proved substantial reliability medially (JSW/mJSW; 0.58/0.051) and laterally (JSW/mJSW; 0.69/0.69). Intrarater

Table 1 Weighted Kappa, with 95% confidence interval, of medial JSW/mJSW and lateral JSW/mJSW. Intrarater, Interrater and test–retest reliability were calculated

= Almost perfect (0,81-1)

= Substantial (0,61-0,8)

= Moderate (0,41 – 0,6)

= Fair (0,21–0,4)

= Slight (0,01–0,2)

Rosenberg

	Medial JSW			Medial mJSW			Lateral JSW			Lateral mJSW		
Intrarater												
Rater	1	2	3	1	2	3	1	2	3	1	2	3
WK	0,89	0,78	0,86	0,88	0,85	0,92	0,80	0,74	0,80	0,71	0,59	0,77
CI	0,84-0,93	0,70-0,85	0,79-0,92	0,83-0,93	0,79-0,92	0,86-0,97	0,70-0,89	0,65-0,82	0,72-0,88	0,60-0,82	0,45-0,72	0,68-0,86
Interrater												
Rater	1vs2	1vs3	2vs3	1vs2	1vs3	2vs3	1vs2	1vs3	2vs3	1vs2	1vs3	2vs3
WK	0,77	0,76	0,73	0,77	0,83	0,79	0,63	0,67	0,68	0,45	0,60	0,42
CI	0,69-0,86	0,67-0,85	0,65-0,82	0,67-0,87	0,75-0,91	0,70-0,87	0,51-0,76	0,54-0,79	0,57-0,79	0,32-0,58	0,47-0,72	0,28-0,55
Test-retest												
WK	0,71			0,74			0,66			0,63		
CI	0,66-0,76			0,69-0,79			0,60-0,73			0,56-0,69		

Varus Stress

	Medial JSW			Medial mJSW			Lateral JSW			Lateral mJSW		
Intrarater												
Rater	1	2	3	1	2	3	1	2	3	1	2	3
WK	0,81	0,75	0,81	0,86	0,80	0,78	0,77	0,70	0,66	0,51	0,47	0,62
CI	0,73-0,90	0,66-0,85	0,74-0,88	0,78-0,93	0,70-0,89	0,70-0,86	0,69-0,85	0,60-0,79	0,55-0,76	0,39-0,63	0,35-0,60	0,50-0,74

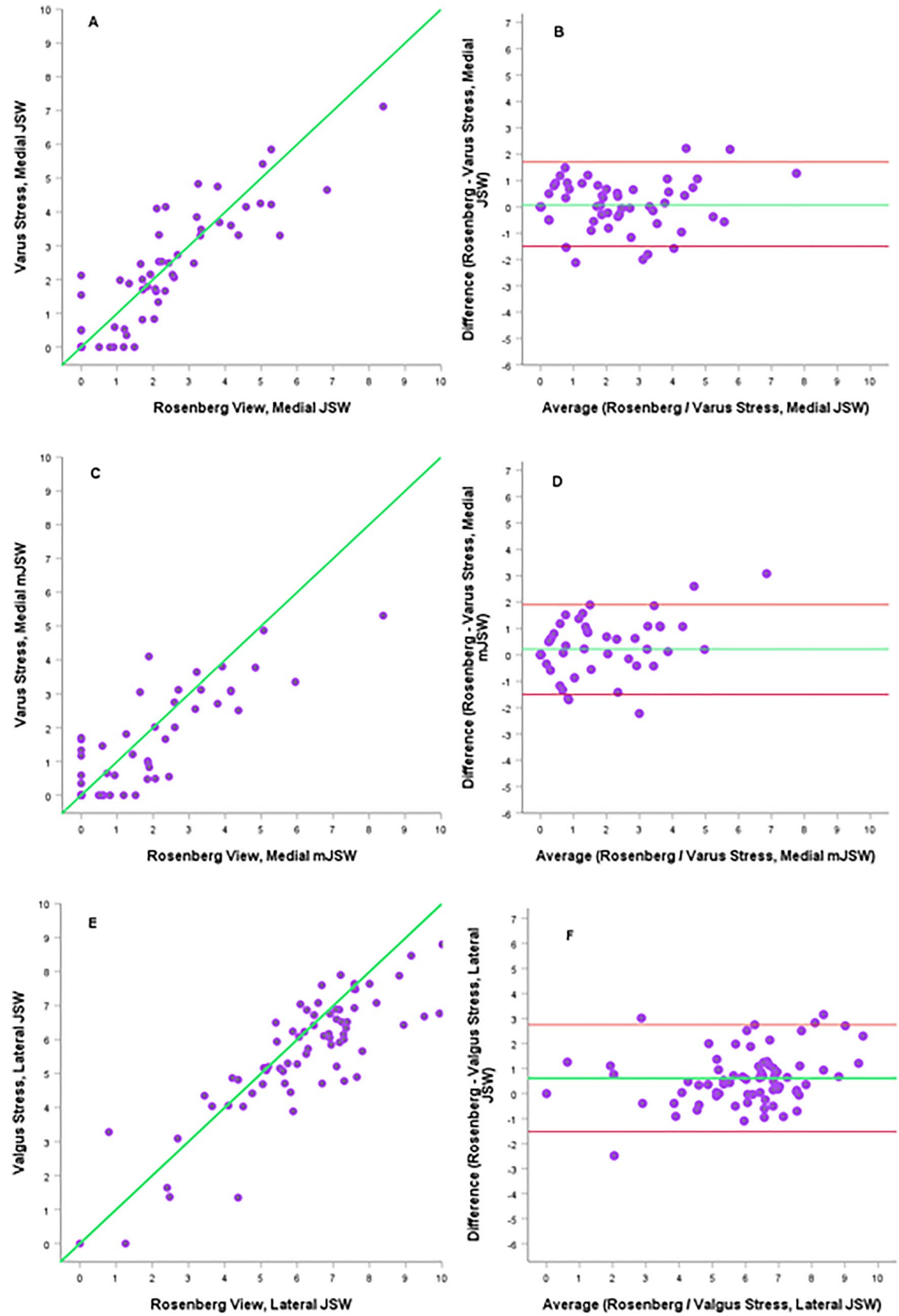
Table 1 (continued)

Interrater												
Rater	1vs2	1vs3	2vs3	1vs2	1vs3	2vs3	1vs2	1vs3	2vs3	1vs2	1vs3	2vs3
WK	0,79	0,72	0,68	0,79	0,77	0,73	0,32	0,49	0,52	0,43	0,34	0,26
CI	0,70-0,88	0,62-0,81	0,58-0,77	0,70-0,87	0,66-0,87	0,62-0,83	0,20-0,44	0,34-0,64	0,40-0,65	0,30-0,55	0,20-0,48	0,13-0,38
Test-retest												
WK	0,71			0,73			0,54			0,45		
CI	0,65 - 0,77			0,47 – 0,62			0,67 – 0,79			0,37 – 0,52		
Valgus Stress												
	Medial JSW			**Medial mJSW**			**Lateral JSW**			**Lateral mJSW**		
Intrarater												
Rater	1	2	3	1	2	3	1	2	3	1	2	3
WK	0,80	0,71	0,73	0,75	0,62	0,73	0,51	0,71	0,75	0,70	0,69	0,77
CI	0,73-0,87	0,62-0,80	0,64-0,82	0,66-0,84	0,51-0,73	0,64-0,83	0,36-0,65	0,61-0,80	0,66-0,84	0,58-0,82	0,58-0,80	0,68-0,85
Interrater												
Rater	1vs2	1vs3	2vs3	1vs2	1vs3	2vs3	1vs2	1vs3	2vs3	1vs2	1vs3	2vs3
WK	0,69	0,70	0,65	0,64	0,69	0,59	0,63	0,65	0,66	0,51	0,64	0,50
CI	0,59-0,79	0,59-0,81	0,55-0,75	0,52-0,77	0,59-0,79	0,44-0,73	0,52-0,74	0,53-0,77	0,54-0,77	0,38-0,65	0,51-0,77	0,37-0,64
Test-retest												
WK	0,58			0,51			0,69			0,69		
CI	0,51 – 0,64			0,43 – 0,58			0,63 – 0,75			0,63 – 0,75		

analysis for valgus stress radiography showed substantial agreement medially (JSW/mJSW; 0.71–0.8/0.62–0.75) and laterally (JSW/mJSW; 0.51–0.75/0.69–0.77). Interrater analysis showed moderate to substantial agreement medially (JSW/mJSW; 0.65–0.7/0.59–0.69) and laterally (JSW/mJSW; 0.63–0.66/0.5–0.64).

Comparison of Rosenberg vs varus & valgus stress

Spearman's rank correlation showed very strong correlation between Rosenberg and varus stress in the medial compartment for JSW ($r=0.91$; CI 0.84–0.95; $p<0.001$), and strong correlation for mJSW ($r=0.81$; CI 0.68–0.90;


A
Varus Stress, Medial JSW
Rosenberg View, Medial JSW
B
Difference (Rosenberg - Varus Stress, Medial JSW)
Average (Rosenberg / Varus Stress, Medial JSW)
C
Varus Stress, Medial mJSW
Rosenberg View, Medial mJSW
D
Difference (Rosenberg - Varus Stress, Medial mJSW)
Average (Rosenberg / Varus Stress, Medial mJSW)
E
Valgus Stress, Lateral JSW
Rosenberg View, Lateral JSW
F
Difference (Rosenberg - Valgus Stress, Lateral JSW)
Average (Rosenberg / Valgus Stress, Lateral JSW)

◂**Fig. 4** The first row showing the medial JSW in varus stress (n = 22 at 0,0 on axis), the 2nd row showing medial mJSW in varus stress (n = 30 at 0,0 on axis), and the 3rd row showing the lateral JSW in valgus stress (n = 1 at 0,0 on axis). Figure A/C/E: scatter plots showing measurements between the Rosenberg view and coronal stress radiography, with the green line representing proportional linearity. Figure B/D/F: Bland–Altman plots showing differences between the two radiographic techniques, with the mean difference (green line), and limits of agreement (red lines)

$p < 0.001$). When comparing medial compartment JSW/mJSW between Rosenberg view and varus stress mean differences of respectively 0.07/0.21 mm (SD 0.82/0.88 mm) was found, $p = 0.45/0.45$ (paired *t* test). Limits of agreement medially were acceptable with JSW/mJSW showing − 1.5 to 1.7/ − 1.5 to 1.9. Strong correlation was seen between Rosenberg and valgus stress in the lateral compartment for JSW ($r = 0.79$; CI 0.66–0.88; $p < 0.001$), and for mJSW ($r = 0.83$; CI 0.71–0.89; $p < 0.001$). Paired *t* tests of the lateral compartment between Rosenberg view and valgus stress showed mean differences in JSW/mJSW of respectively 0,62/0,45 mm; SD 1,1/1,1 mm; $p = 0.0001/0,001$, with valgus stress measuring lower cartilage height (see Fig. 4). Limits of agreement laterally were wider than medially, showing − 1.6 to 2.6 mm for mJSW, also confirming valgus stress measuring lower height. Scatterplots visualizing the linear relationship between the abovementioned comparisons, along with Bland–Altman plots with a mean difference close to zero, relatively acceptable limits of agreement, and a consistent variability can be seen in Fig. 4.

Discussion

The main findings of this study are that the Rosenberg view and standardized coronal stress radiographs are reliable in technical execution/setup, with good observer agreement, and that they provide similar measurements of cartilage height both medially and laterally.

When performing measurements of joint space widths, there is a risk, that positioning may make assessments unreliable. We examined the reproducibility of two important techniques for measuring joint space widths of the knee by taking two sets of radiographs separated by a two-minute break, where the patient was asked to move about. Analyses of measurements comparing the two sets of radiographs showed overall substantial reliability. The setup was described in detail in the written instructions used by the radiographer, and it is reasonable to believe that this mitigates any variation that might be introduced by different radiographers. The effect of different radiographers, was however, not investigated in this study. The time interval between the two sets of radiographs was only minutes, which is substantially shorter than other test–retest comparisons, e.g. Segal et al. [25], but we believe that stepping off the examination table and moving about is more important than the length of time between the examinations. Koppens et al. [26] have found similar reliability for JSW measurements medially and laterally for valgus stress radiographs. In a similar study measuring coronal laxity following total knee arthroplasty, Kappel et al. [27] found excellent reliability for angular measurements using the stress device. In consequence, we believe that it is fair to claim, that the test–retest reliability of stress radiography is high, if a standardized protocol is used. We have not been able to find any publication on the test–retest reliability of the Rosenberg view.

Aside from the technical setup, it is also important that observers are in an acceptable range of agreement, both with each other and themselves. We investigated this by comparing the observers' observers intrarater double measurements and also comparing interrater measurements. We found substantial to almost perfect intra- and interrater agreement for measurements of the medial compartment for varus stress and Rosenberg views. Another finding was the difference in mJSW and JSW, where bone-on-bone was discovered more often when using mJSW instead of JSW for determining the cartilage height. Bone-on-bone was found medially in 30/73 participants compared to 22/73 when using mJSW compared to JSW, respectively. This is important in determining the presence of bone-on-bone and suitability for mUKR [2, 8], as unfavorable results have been reported for cases with only partial-thickness cartilage loss [12].

As for the lateral compartment, we showed moderate to substantial intra- and interrater agreement between Valgus stress and Rosenberg view, which are similar results to the study from Koppens et al. [26]. Albeit, our study showed that slightly better agreement was found when using JSW as a measurement of cartilage height laterally, instead of mJSW which is more subjective to the observer as seen in the presented inter- and intrarater agreement (see Table 1). This could indicate that standardized approaches to cartilage height measurements are better in areas with slightly incongruent anatomical features, such as a convex lateral tibial plateau [28].

A sufficient medial opening during valgus stress is also important to rule out varus deformities that are incorrectible [8]. This study has shown that during valgus stress, medial JSW would be better than mJSW as a measurement for medial opening, since showing more substantial results of inter- and intrarater agreement between Rosenberg and valgus stress radiography. This is also likely because JSW is a well-defined and standardized measurement when opening a knee compartment, compared to mJSW. Koppens et al. again showed similar results in this regard [26]. Even though measurements of the medial compartment in valgus stress prove to be accurate and precise, the use of valgus stress has been questioned. Kreitz et al. conclude that valgus stress radiographs have an overstated value in the workup for mUKR since the full extent of varus deformity cannot be determined until after removing osteophytes peroperatively [29].

The cartilage height measurements were either strongly or very strongly correlated, when comparing Rosenberg to varus or valgus stress in each relevant compartment. Minor systematic errors were present, with acceptable limits of agreement medially for JSW/mJSW seen as – 1.5 mm to 1.7 mm/ – 1.5 to 1.9 mm. Laterally we found less acceptable limits of agreement for JSW, proven to be – 1.5 to 2.8 mm with a mean difference of 0,62 mm for JSW (see Fig. 4). The accuracy between these techniques is therefore high, but precision less so. Whether this difference is clinically relevant in determining lateral JSW remains to be established, since both techniques have roughly the same precision. This is important, since the presence of lateral full-thickness cartilage is a necessity when considering a mUKR [8], and our study shows that these techniques have strongly correlated measurements, and also have relatively similar accuracy and precision.

It also seems unlikely that a 0,62 mm difference in lateral JSW would influence the decision on whether to proceed, if aiming for a mUKR. The high correlation between techniques is quite surprising, as each technique represents a knee flexion of either 20 or 45 degrees, while still detecting bone-on-bone medially and full-thickness cartilage laterally.

Standardized stress radiography is a highly reproducible technique compared to manually performed stress in various ways [30–34]. The disadvantages of using a standardized stress device are the cost of the equipment itself, the need for specialized and trained radiographers to perform the technique, along with the time consumption of setting up the device twice to achieve radiographs in both varus and valgus. Disc omfort from the Telos stress device on some of the patient’s knees can also pose a disadvantage, but this was only considered a moderate problem.

The Rosenberg view does not need extra specialized equipment, which is especially an advantage in centers without the equipment and trained personnel. It has been used as an extra diagnostic tool when considering patients for a mUKR [12]. Another advantage of the Rosenberg view is its higher specificity and sensitivity compared to conventional anteroposterior radiography [7], possibly suggesting that the Rosenberg view could save the additional cost and radiation of a conventional anteroposterior radiograph, and two additional coronal stress radiographs. This study group suggests that a standing Rosenberg view is sufficient to determine suitability for a mUKR, if ligament stability and correctability is normal. In cases of conflicting clinical and radiographic findings, especially in the lateral knee compartment additional imaging may still be indicated. During the workup for a mUKR, lateral projections and Skyline radiography are still necessary despite these findings [8]. Future research should focus on investigating the possibility of achieving a higher precision of lateral cartilage height measurements with radiography.

Limitations

Observer fatigue could influence the results since the measurement process lasted many hours over many days. Raters who know they are being observed may modify an aspect of their behavior in their awareness of being observed (Hawthorne effect). Diagnostic screens were not used in the x-ray analysis.

Conclusion

Both the Rosenberg view and coronal plane stress radiography methods were found to have high reliability and agreement when measuring articular cartilage thickness in assessing the presence of bone-on-bone medially and full-thickness cartilage laterally. Strong to very strong correlation was found when comparing measurements between the Rosenberg view and coronal stress radiographs. Therefore, we conclude that both techniques are valid and interchangeable in the work-up for mUKR, but may in some cases need to be supplemented with each other or alternatively use magnetic resonance imaging. Each technique has their advantages and disadvantages, but the Rosenberg view could help to save costs on equipment, specialized personnel, and excess radiation compared to standardized stress radiography.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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MRi of the knee compared to specialized radiography for measurements of articular cartilage height in knees with osteoarthritis

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ABSTRACT

This study aims to evaluate and compare extremity-MRi with specialized radiography by measuring articular cartilage height in patients with knee osteoarthritis.

A prospective study, including sixty patients. Measurements on MRi images, Rosenberg view, and coronal stress radiographs were performed. MRI was compared to specialized radiography.

Measurements in the medial compartment showed negligible/weak correlation between MRi and Rosenber/varus stress. In the lateral compartment, MRi and the Rosenberg/valgus stress view were strongly correlated.

We conclude that MRi cannot replace radiographs for the measurement of articular cartilage thickness. MRi should, however, be reserved for more unusual cases of atypical clinical findings.

1. Introduction

To ensure the correct knee implant for the right patient, it is essential to know how different imaging types discriminate between the levels of degenerative disease in the different compartments. To support the correct choice of imaging technique, it is essential to know whether levels of degenerative disease are better visualized using magnetic resonance imaging (MRi) compared to specialized radiography, such as the Rosenberg view and coronal stress radiography.

MRi has long been considered the gold standard for evaluating soft tissue, articular cartilage, and early osteoarthritic (OA) changes. Still, the usefulness in detecting severe OA is less clear.[1] In clinical practice, MRi is generally not included in the decision-making process when considering knee arthroplasty surgery. It has been criticized in the work-up for knee replacements due to the over-estimation of knee pathology, pricing, and time consumption in healthcare systems where cost efficiency is essential. Although some areas of the world see an increasing use of MRi for endstage knee OA, this possible rise in costs could be minimized when using an extremity-MRi scanner, which is cheaper. Though, this often is accompanied by imaging with lower field strength and resolution on the acquired images.

Conventional radiography of the knee is considered sufficient when offering a total knee replacement (TKR), but complementary specialized radiographs may be necessary when considering a medial

Abbreviations: JSW, Joint space width; mJSW, minimal Joint space width; MRi, magnetic resonance imaging; mUKR, Medial Unicompartmental Knee Replacement; OA, Osteoarthritis; TKR, Total Knee Replacement.

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unicompartmental knee replacement (mUKR).[2–4] Specialized radiography visualizing the tibiofemoral compartment includes the Rosenberg view and coronal stress radiography, recommended in various radiographic algorithms.[5,6] This study set out to compare some of these specialized radiographic techniques with proton density fast spin-echo (PD-FSE) MRi in patients undergoing either a mUKR or TKR.

Only limited information is available regarding articular cartilage height measurements using MRi, and studies comparing MRi with specialized radiography are scarce. This type of study can provide the essential information needed in choosing the optimal diagnostic tool to diagnose the specific type of knee osteoarthritis present, potentially avoiding excess radiation and extra costs in the diagnostic process.

This study aimed to assess the interrater agreement of MRi in a cohort of patients with knee osteoarthritis and compare if MRi and specialized radiography can determine the tibiofemoral joint space width similarly.

2. Patients and methods

Guidelines for reporting reliability and agreement studies (GRRAS) were followed[7] in this prospective diagnostic study. The “STROBE” statement and guidelines were followed.[8]

2.1. Patients and population

One hundred and sixty patients were asked to participate in this study at a high-volume knee arthroplasty centre. Sixty patients participated in this substudy between October 2018 and June 2019. Participants had both an MRi scan and specialized radiography of the knee. Eighty-seven patients declined participation, and thirteen only had radiographs performed due to delay of technical setup of the MRi. All sixty patients participated in a separate radiographic study investigating the reliability and agreement of articular cartilage height measurements with the 45° Rosenberg view and 20° coronal stress radiographs. Thirty-three were planned for TKR, and twenty-seven were planned for mUKR (twenty-nine females and thirty-one males). A patient flowchart can be seen in Fig. 1.

The only inclusion criterion was being planned for either a TKR or a mUKR at the enrollment time. The patients selected for inclusion were random and unselected, forming a convenience series depending on the

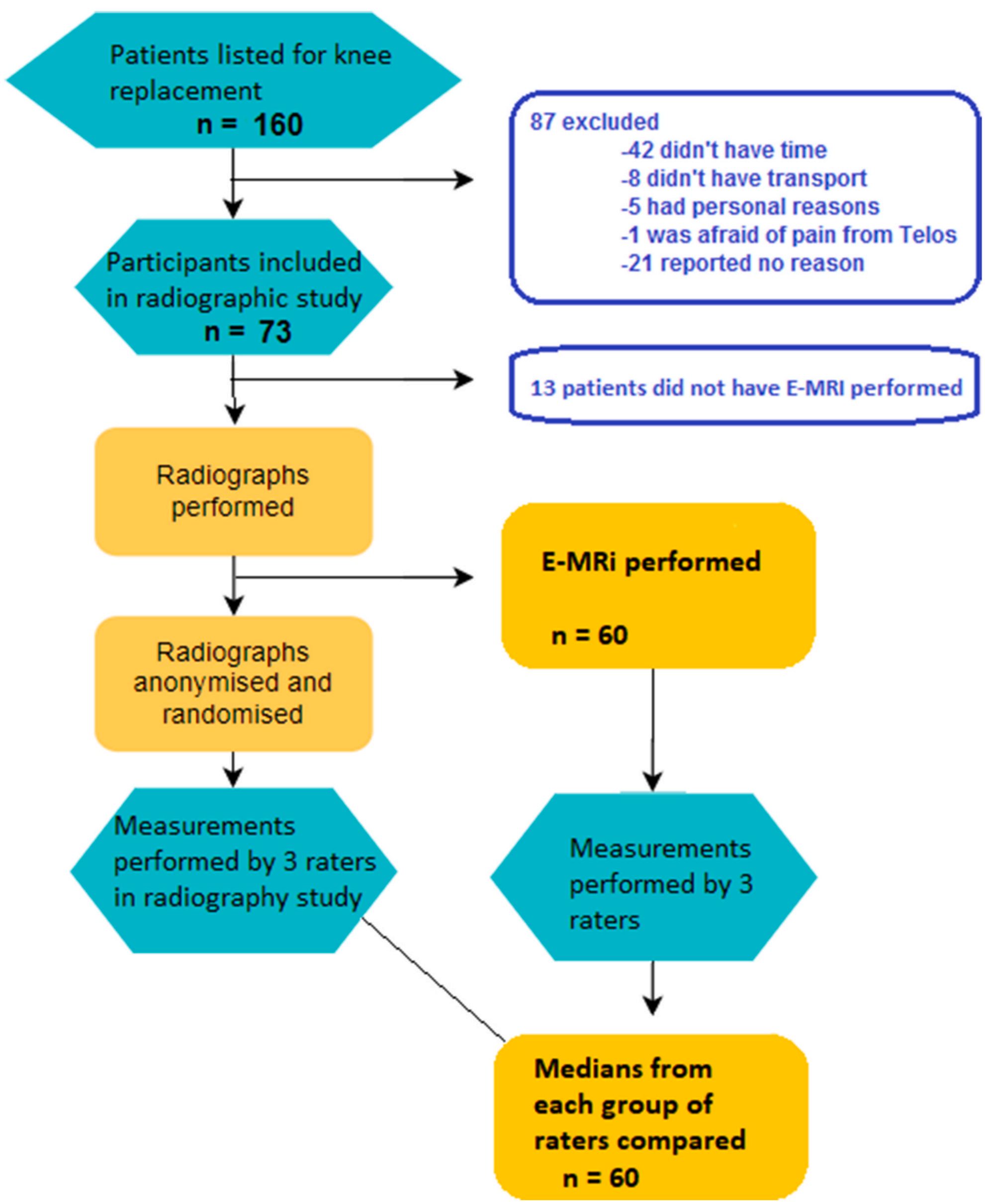

Fig. 1. Flowchart.

radiographic ward's capacity. Exclusion criteria were pregnancy, severe systemic disease, employment at the department, a lack of ability to comply with simple instructions, and common contraindications for performing MRi, such as having a pacemaker or other metallic implants.

2.2. Methods of testing

2.2.1. Radiographs

One experienced radiographer performed all radiographic examinations, using a Siemens Axiom Luminos dRF with fluoroscopy (Siemens Healthcare GmbH, Erlangen, Germany). The focus was set to Fine, with an opening of 0.6 mm. A sequence of radiographs was performed for each patient, consisting of the Rosenberg view, followed by coronal stress in varus and valgus (performed in a twin study, pending publication).

2.2.2. MRi

An Optima MR 430s 1,5 T extremity MRi scanner was used for this study. The patients were positioned in a chair in a reclined position outside of the scanner. Only the patients' knee was placed inside the scanner. The knee was positioned in the coil with 0–5° flexion, without weight-bearing, as this has proven to show similar cartilage thickness as weight-bearing MRi.[9] The knee protocol includes proton density (PD) weighted sequence with and without fat saturation in coronal and axial plains. Technical information for Coronal/Axial planes: Slice thickness 3.5/4.5 mm; Gap - 1/1.5 mm; Matrix - 512 × 512 for both planes; FOV - diameter 160mm/150 mm; TR - 1652/1682 ms; TE - 21.8/22.2 ms; NEX - 2 for both planes.

2.3. Methods of assesment

2.3.1. Radiographic measurements

Magnification calibrated, anonymized, and randomly ordered measurements of the radiographs were used from three individual raters, consisting of consultant orthopedic surgeons. The median of the three raters' measurements was calculated for each parameter, using the first of three rounds of measurements. Parameters consisted of central joint space width (JSW) and minimal joint space width (mJSW), measured in millimeters with one decimal in each tibiofemoral compartment for each type of specialized radiograph (see Fig. 2) (performed in a twin study, pending publication).

2.3.2. MRi measurements

Four sets of images on PD-FSE images in coronal and axial planes, with and without fat saturation, per scanned knee, were obtained and

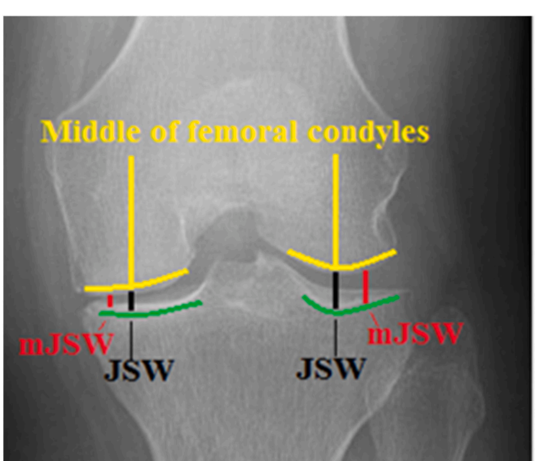

Fig. 2. Radiographic measurements of JSW and mJSW in specialized radiographs.

reviewed on an IMPAX Site working station 6.6.1.8006 (Agfa-Gevaert, Mortsel, Belgium). Orthopedic resident, a Radiology resident, and a certified radiologist with seven years' experience as a musculoskeletal imaging consultant. The medians of the three raters' measurements for each parameter were used. Measurements were primarily conducted on the PD-FSE image without fat-saturation, and images with fat-saturation were used to help confirm difficult measurements.

Articular cartilage height was measured in both the medial and lateral tibiofemoral compartment. Each knee compartment was assessed by measuring the femoral and tibial bone-cortex distance in the compartment, which was considered the JSW. Measurements were also performed at the smallest distance perceived (mJSW) between the femoral and tibial bone cortex at a weight-bearing location, seen in Fig. 3A+B. No attempt was made at measuring the individual cartilage heights of femoral or tibial surfaces, as this was not accurately feasible due to the low pixilation and slice width.

2.4. Statistics

Data presented itself as right-skewed and clustering towards zero. Therefore data used for reliability analysis was rounded to the nearest integer, and non-parametric weighted Cohen's Kappa was used to determine agreement and reliability. SPSS statistical package version 22 (IBM SPSS Inc, Chicago, IL) and Microsoft Excel (Microsoft Corporation, Washington, USA) with Realstatistics-data-analysis-tool add-in were used to calculate linear weighted kappa with 95% confidence interval. Strength of agreement and reliability were categorized as follows; Poor (<0.00); Slight (0.00–0.20); Fair (0.21–0.40); Moderate (0.41–0.60); Substantial (0.61–0.80); Almost perfect (0.81–1.00).[10] Data used to compare radiographic techniques to MRi measurements consisted of the medians of the three raters' measurements for each measurement type (see flowchart in Fig. 1). Spearman's rank correlation coefficient was used to summarise the strength of the relationship between the radiographic techniques and the MRi measurements and was interpreted as follows; Negligible (0–0.1); Weak (0.1–0.39); Moderate (0.4–0.69); Strong (0.7–0.89); Very strong (0.9–1).[11] Mean difference and limits of agreement were analyzed using Bland-Altman plots, along with scatterplots to show the strength of agreement between variables.[12] Comparison of demographic data was made using the Student's T-test. A comparison of means between techniques was made using a paired T-test.

3. Results

Demographics of sixty included patients, showed a mean age of patients 71 ± 8 years with no difference between sexes ($p = 0.9$) and implant types ($p = 0.4$). The mean BMI was 28 ± 4 kg/m^2, with no difference between sexes ($p = 0.4$) and implant types ($p = 0.5$).

3.1. Specialized radiography agreement and reliability

All raters and participants completed the protocol.[13] In this study (n = 60), mean measurements were calculated for each technique in each compartment. For the Rosenberg view, mean measurements of JSW (SD)/mJSW(SD) were 1.6(1.6)/1.1(1.4)mm in the medial compartment and 6.4(1.9)/5.5(2.0)mm in the lateral compartment. For coronal stress radiography, mean measurements were 1.6(1.7)/1.0(1.3)mm in the medial compartment in varus stress and 5.9(1.6)/5.1(1.7)mm in the lateral compartment in valgus stress.[13]

3.2. MRi agreement

Mean measurements of JSW(SD)/mJSW(SD) were 1.9(1.0)/0.9(0.6) mm in the medial compartment, and 4.3(1.6)/3.7(1.5)mm in the lateral compartment. Interrater analysis for MRi showed primarily fair to substantial agreement medially (JSW/mJSW; 0.46–0.64/0.38–0.62) and

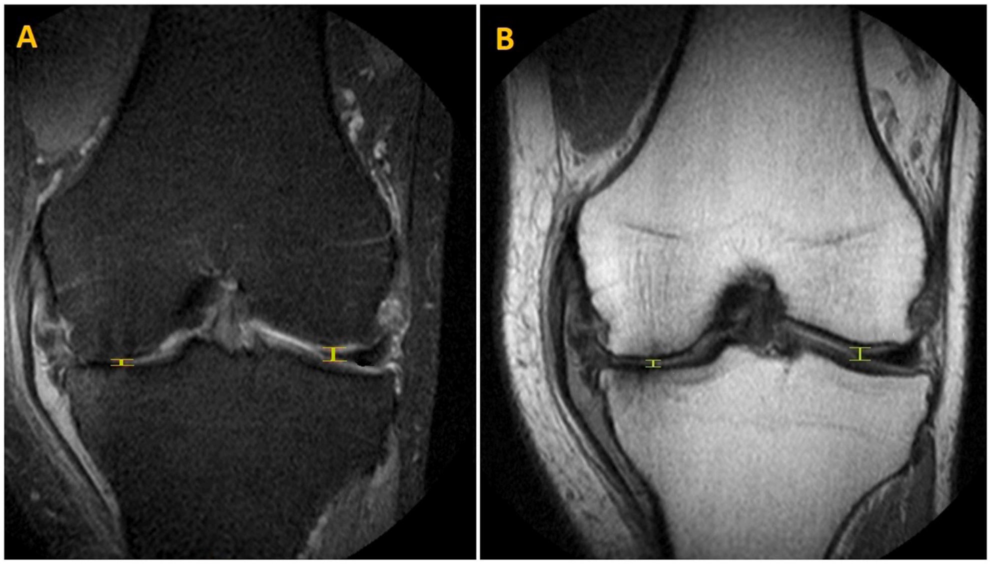

Fig. 3. MRi scanning using PD-FSE imaging with fat saturation (A) and without fat saturation (B), showing the standardized central measurement of the articular cartilage height in the tibiofemoral joint medially and laterally, measured as JSW.

moderate to substantial agreement laterally (JSW/mJSW; 0.44–0.53/0.46–0.61), which can be seen in Table 1.

3.3. MRi vs. specialized radiography

3.3.1. Medial compartment

Comparing MRi measurements with the Rosenberg view showed negligible to weak correlation medially (JSW/mJSW; r = 0.07/0.22; CI = −0.17–0.33/-0.06–0.48; p = 0.3/0.042) which was non-significant. Comparing MRi measurements with the varus stress radiography showed weak correlation medially (JSW/mJSW; r = 0.11/0.15; CI = −0.18–0.36/-0.23–0.41; p = 0.19/0.31) which was also non-significant. Scatterplots can be seen in Fig. 4.

3.3.2. Lateral compartment

Comparing MRi mJSW measurements with the Rosenberg view showed strong correlation laterally (JSW/mJSW; r = 0.74/0.79; CI = 0.58–0.85/0.67–0.87; p = 0.001) which were both highly significant. Comparing MRi mJSW measurements with the valgus stress radiography showed strong to very strong correlation laterally (JSW/mJSW; r = 0.82/0.77; CI = 0.68–0.90/0.62–0.87; p = 0.001) which were both highly significant. Scatterplots and Bland Altmann plots show systematically and consistently lower measurements with MRi, with a mean difference ranging from 1,5 to 2 mm, and limits of agreement ranging relatively widely (see Figs. 5–6).

4. Discussion

4.1. MRi vs. specialized radiography

4.1.1. Medial tibiofemoral compartment

No significant correlation was found between MRi and specialized

Table 1
Weighted Kappa, with 95% confidence interval, of MRi interrater agreement in the medial JSW/mJSW and lateral JSW/mJSW.

MRi interrater agreement						
	Medial JSW			Medial mJSW		
Raters	1vs2	1vs3	2vs3	1vs2	1vs3	2vs3
WK	0,61	0,46	0,64	0,44	0,38	0,62
CI	0,51-0,71	0,34-0,59	0,52-0,76	0,26-0,63	0,17-0,59	0,45-0,8
	Lateral JSW			Lateral mJSW		
Raters	1vs2	1vs3	2vs3	1vs2	1vs3	2vs3
WK	0,47	0,44	0,53	0,46	0,47	0,61
CI	0,32-0,61	0,3-0,58	0,42-0,64	0,31-0,6	0,34-0,6	0,49-0,72

= Almost perfect
= Substantial (0,61-
= Moderate (0,41 –
= Fair (0,21–0,4)
= Slight (0,01–0,2)

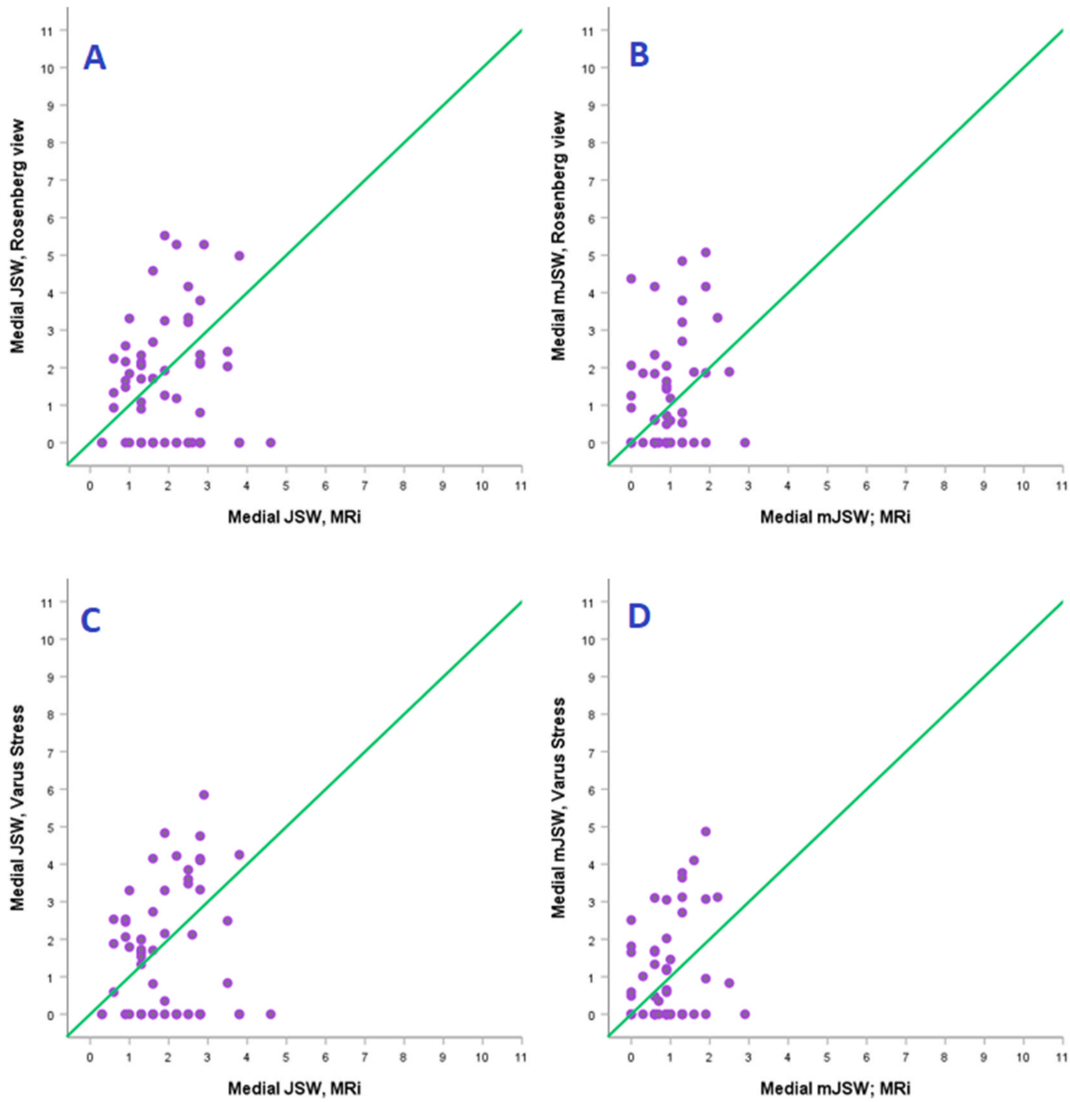

Fig. 4. Medial knee compartment - Scatterplots of MRi vs. specialized radiography in measuring JSW/mJSW.

radiography when measuring JSW/mJSW in the medial knee compartment. Scatterplots showed that many patients presented with bone-on-bone in the medial compartment with the Rosenberg view and varus stress JSW/mJSW but were measured with several millimeters of cartilage on MRi (see Fig. 4). These larger measurements on MRi were seen more so when using JSW than mJSW. These results could be explained by the knee's position in 0–5° flexion compared to 20–45° flexion using specialized radiographs. Also, the lack of weight-bearing could result in measurements of more than just articular cartilage, but earlier studies of weight-bearing vs. non-weight-bearing MRi have shown this to be of minimal difference.[9] This is the clinical reality when using MRi. It is typically impossible to have MRi performed with weight-bearing or a higher flexion of the knee due to the coil's placement around the lower extremity. These findings represent a significant concern of MRi's ability to assess cartilage height in late-stage OA knee compartments since half of the study population presented with isolated medial OA. This is further supported by the lack of correlation to the specialized radiographs in the medial compartment.

Altogether, this study's findings show that MRi is not suited for diagnosing bone-on-bone and endstage OA in the medial knee compartment. This can be regarded as a positive finding since it should further discourage using an expensive imaging technique such as MRi for solely to confirm medial bone-on-bone OA. Furthermore, it should be discouraged when bone-on-bone can be assessed sufficiently with a cheap and straightforward radiographic image such as the Rosenberg view or varus stress radiography.[13]

4.1.2. Lateral tibiofemoral compartment

A strong to very strong correlation was found between MRi and specialized radiography in the lateral compartment. Valgus stress measurements compared to MRi (JSW) showed the best correlation ($r = 0.82$), albeit valgus stress mJSW and the Rosenberg view also with high correlation ($r = 0.74$–0.79).

When analyzing the scatterplots and Bland Altman plots, we saw that MRi consistently measured 1.5–2 mm smaller JSW/mJSW than both special radiographic techniques. When considering offering a mUKR, full-thickness cartilage should be present.[5,14] Considering this correlation between techniques and the small difference in measurements between specialized radiographs and MRi, we can conclude that both types of specialized radiography and MRi can be used to confirm full-thickness cartilage in the lateral compartment. This should further discourage the use of MRi for general screening of patient suitability for mUKR in regards to cartilage height assessment.

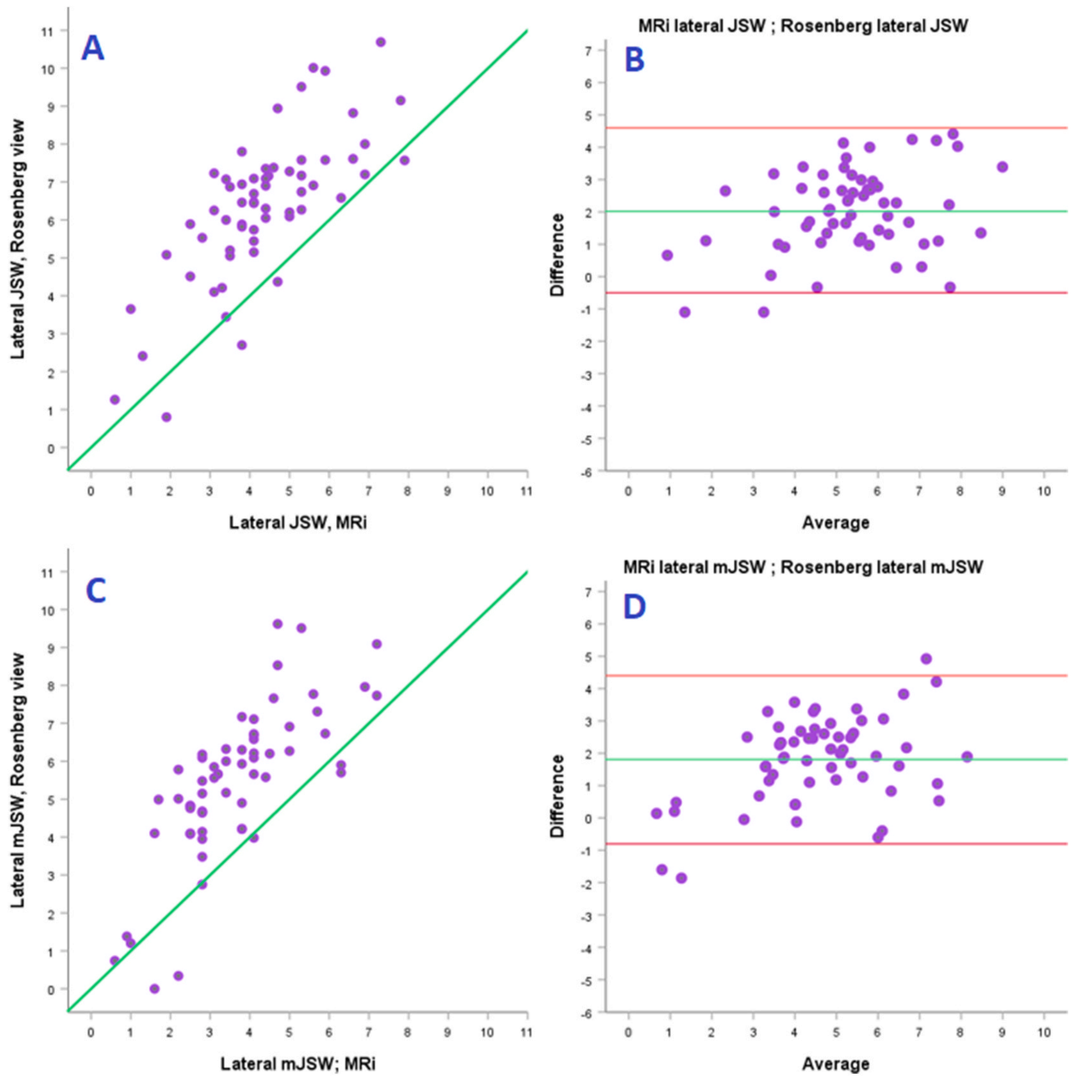

Fig. 5. Lateral Knee compartment - Scatterplots (A + C) and Bland Altmann plots (B + D) comparing the Rosenberg view to MRi in measuring JSW/mJSW.

4.2. MRi

We found moderate to substantial agreement between all raters on MRi measurements, except for one category between rater 1 and 3 (Medial mJSW), showing that overall agreement was acceptable. Previous studies have generally proven good inter- and intrarater agreement when assessing the knee's cartilage status.[15] However, studies are scarce in comparing raters in the measurements of tibiofemoral JSW and mJSW on extremity MRi. Performing test-retest measurements were considered redundant with MRi, as previous studies have shown high reliability, even when comparing with different field strengths.[16] When reviewing the current literature, no other studies have compared the Rosenberg view and coronal stress radiography with MRi, in a larger population of patients with endstage OA, listed for either a mUKR or TKR. This study has shown that the low tesla MRi is a good tool for visualizing the height of intact cartilage laterally, but that this is similarly done with the Rosenberg view or valgus stress radiography. It also shows that MRi is quite unreliable when assessing cartilage height in significantly deteriorated knee compartments. This should be considered when using MRi for general screening of patients for mUKR, as both of these assessments can be done on specialized radiographs similarly.

4.3. Limitations

MRi scanning of the knee joint was performed in the axial and coronal plane due to the study's time and practical limits, but imaging in two planes was considered sufficient for the study. The use of a 1.5 T extremity scanner may present a limitation on the quality upon which the imaging is measured due to larger pixel size and lower definition. Optimally, automated software for JSW/mJSW-detection and measurement would be used in such a study[17] but was not feasible in this study. Measurement of the cartilage thickness on each bone surface would be a better method of assessing the correct total cartilage thickness in each compartment, but this was not possible in knees with very deteriorated cartilage. Therefore, MRi measurements from cortex to cortex of both JSW/mJSW were considered the best measurement method in this study to compare with radiographic JSW/mJSW. The knee joint was not in a weight-bearing position when performing MRi, theoretically allowing the possibility of fluid to enter the compartment between the joint surfaces, but this was not an actual issue during measurements. In some cases, this could increase the measured JSW/mJSW, but earlier studies have shown this to have a marginal impact.[9] The knee was positioned in different degrees of flexion in each method, but this reflects general clinical practice.

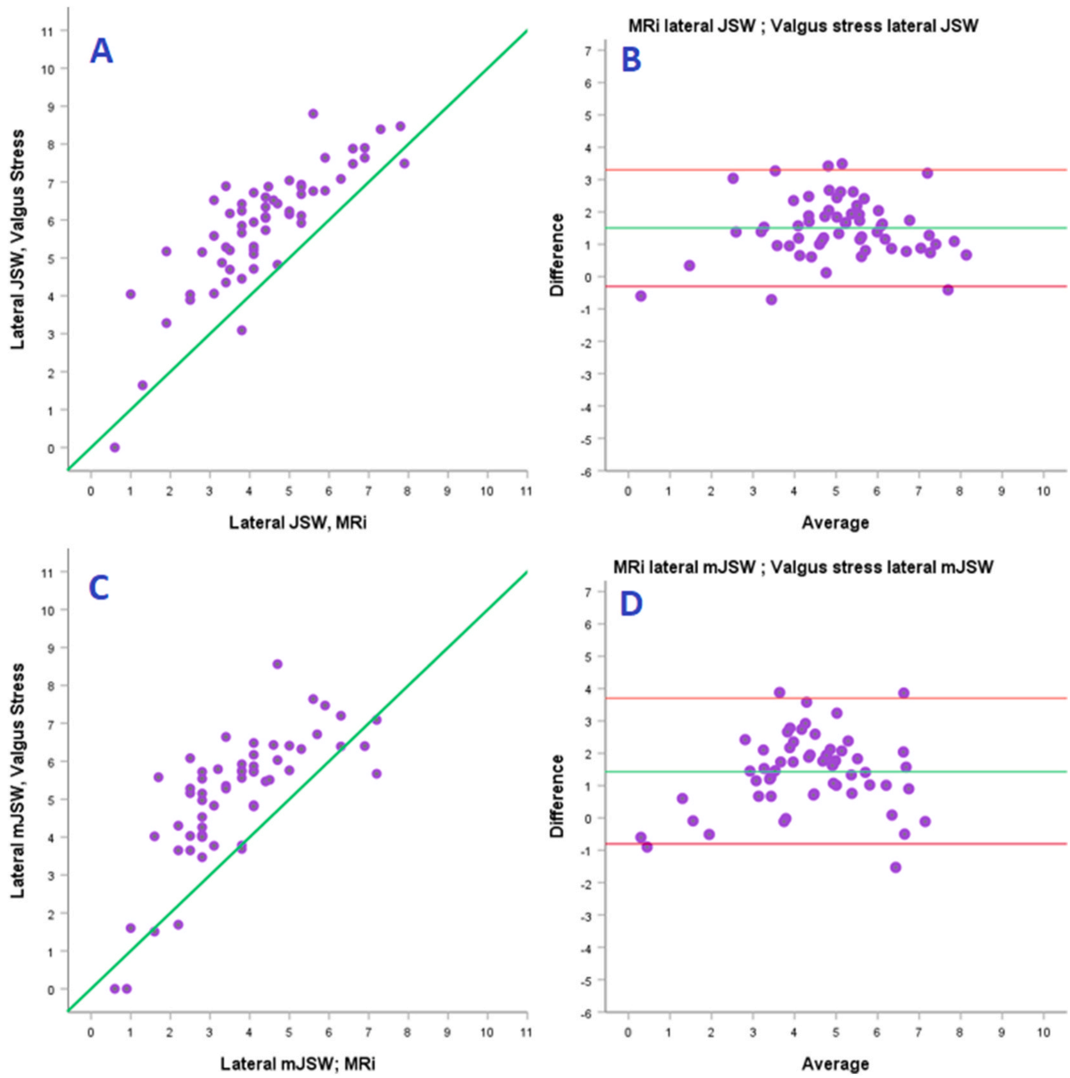

Fig. 6. Lateral Knee compartment - Scatterplots (A + C) and Bland Altmann plots (B + D) comparing valgus stress to MRi in measuring JSW/mJSW.

5. Conclusions

Non-significant weak correlation was found between specialized radiography and MRi when measuring cartilage height in the medial knee compartment. A strong to very strong correlation was found between specialized radiography and MRi in the lateral compartment. We conclude that MRi cannot and should not replace these specialized radiographic methods but should be reserved for more special cases where abnormal radiography or suspicion of atypical clinical findings present themselves.

Ethical policies

Participants gave informed consent before inclusion, and the study has obtained approval from the Danish Ethics Committee, approval-id H-18010291.

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An Investigation of Medial Tibial Component Overhang in Unicompartmental and Total Knee Replacements Using Ultrasound in the Outpatient Department

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Abstract

Tibial component overhang is known to be a contributor to worse outcomes in knee arthroplasty. The aim of this study is to investigate the presence of tibial component overhang, and whether overhang correlates to a higher local tenderness in both medial unicompartmental and total knee replacements. Also, to determine if a rotational projection phenomenon is presented with radiographs when investigating tibial component overhang. A prospective study, including 64 participants, was performed, where ultrasound measurements were compared with postoperative radiographs. Local tenderness was measured as a pressure pain threshold, determined at 3 months postoperatively using algometry. Sixty-two of sixty-four patients had an underdiagnosed medial overhang on radiographs, with a mean difference of 2.4 mm between radiographs and ultrasound ($p < 0.001$), presenting a rotational projection phenomenon. When comparing sites with ultrasound measured overhang to sites without overhang measured by ultrasound, a higher local tenderness was observed ($p < 0.001$). A positive linear correlation was found between patients' overhang and local tenderness ($r = 0.2$; $p = 0.045$). Subgroup analysis of medial overhang showed significantly higher tenderness than all other locations. No significant differences were seen for lateral overhang. An apparent rotational projection phenomenon of overhang on radiographs was seen, and a linear association between overhang and local tenderness was demonstrated. This study warrants the use of ultrasound when a surgeon is presented with a patient with postoperative medial tenderness, but no overhang can be seen on radiographs. It should also raise awareness of implant selection and positioning during surgery, especially avoiding the overhang to be localized directly medially.

Keywords

- knee
- arthroplasty
- ultrasound
- overhang
- radiography

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Tibial component overhang caused by oversizing or malpositioning is sometimes observed following unicompartmental (UKR) and total knee replacements (TKR).[1,2] The overhang may, in turn, lead to soft tissue irritation and local medial or lateral tenderness.[1,3–5] In rare cases, it can cause pes snapping syndrome[6,7] or fabella syndrome.[8,9]

The definitions, limits, and incidences of overhang vary among studies.[2,10–13] Furthermore, different associations of patient-reported outcomes, pain scores, and knee flexions are associated with overhang.[1,2,5,10,11,14,15] The present literature is equivocal on the presence and effect of overhang. This lack of consensus could be due to different limits of acceptable overhang, whether overhang is defined as present or not, the method of measurement of overhang, the potential influence of the rotational projection phenomenon, or a combination of the abovementioned.

Conventional radiographic examination of knee replacements can be unreliable in determining tibial component overhang because of the rotational projection phenomenon,[16] that is, errors introduced by the projection angle relative to the overhang. Using ultrasound (US) to visualize bone-surfaces is increasing in popularity[17] and has the potential to precisely identify the location and size of overhang and can be an efficient, cheap, and secure method of investigating an overhang. US has been shown to allow good assessment of orthopaedic hardware and surrounding tissues,[18] but there are no published studies on the assessment of tibial component overhang. The main concept of this is to detect the metal tibial component adjacent to the proximal tibial cortex, thereby measuring the tibial component overhang.

Local tenderness may be quantified as the threshold at which pressure is experienced as pain, that is, a pressure pain threshold (PPT). A low PPT signifies a high level of tenderness. Methods for measuring PPT are well described, and sound measurement properties have been observed in various patient groups, including knee osteoarthritis patients.[19–22]

This study aims to investigate tibial component overhang using US in both total knee and medial UKRs. We intended to answer whether US-measured overhang is associated with local tenderness, as measured by PPT. We also intended to compare overhang measured by US and conventional radiography.

Materials and Methods

Sixty-four patients (64 knees) were prospectively included over a 10-month period (August 2018 to May 2019) when arriving at one high-volume knee replacement outpatient clinic for their regular 3-month follow-up appointment after receiving either a TKR or a medial UKR (see ►**Fig. 1**). The included participants formed a convenience series, mostly depending on the corresponding author's presence in the outpatient clinic, while some patients declined participation because of time constraints ($n = 7$). In this time period, the corresponding author was in the outpatient department 45 days, out of a total of 217 workdays. During this period, 983 patients underwent primary knee replacement surgery, by a total of 13 knee surgeons. Patients were included prospectively without any systematic selection, except for the selection of 50% male/50% female and 50% TKR/50% UKR, creating four equal-sized groups. When each of these groups was filled up, screening and inclusion for the group stopped. The highly experienced surgical team was the same for both UKRs and TKRs. UKR implants consisted of either Oxford medial partial knee arthroplasty ($n = 23$) with mobile bearing (Zimmer Biomet, Bridgend, UK), and the Zimmer unicondylar knee system ($n = 9$) with fixed bearing (In Denmark supplied by Lima Denmark ApS, Nivå, Denmark). TKR implants consisted of PFC-Sigma cruciate retaining implants (DePuy Synthes, Raynham, MA). The patients' age, weight, height, and type of knee replacement were recorded. Each patient first had their local tenderness assessed, followed by US measurements.

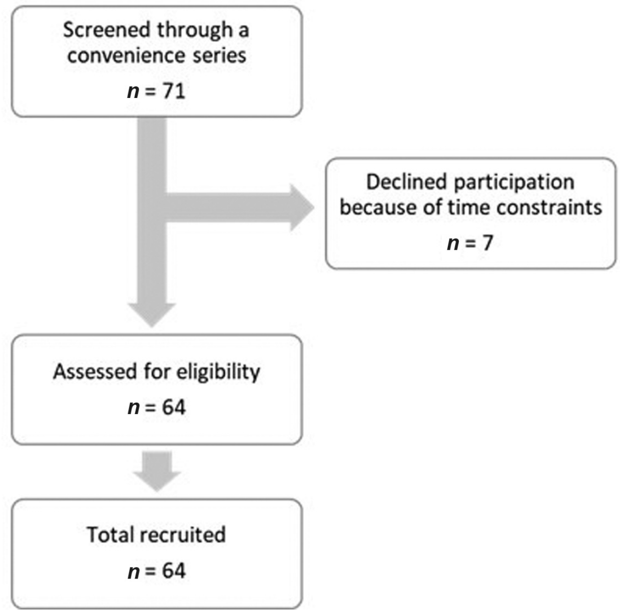

Fig. 1 The study flowchart.

Ultrasound

Patients were asked to sit semi-recumbent with their knee flexed to 90 degrees for the US and PPT measurements. The knee joint and tibial component were palpated to localize 5 or 10 different measurement sites for UKR or TKR, respectively (►**Fig. 2**). The anteroposterior axis was identified by palpation, and medial sites were chosen (45 degrees; 67.5 degrees; 90 degrees; 112.5 degrees; 135 degrees), and the lateral sites (225 degrees; 247.5 degrees; 270 degrees; 292.5 degrees; 315 degrees) were chosen relative to this, as precisely as possible with visualization of anatomical landmarks. The same observer recorded US measurements and PPTs. The US apparatus used was a Sonosite M-Turbo (Fujifilm Sonosite, Inc., WA), using the musculoskeletal probe (HFL38X) with a frequency of 13 to 6 MHz.

Patients were scanned with US at each measurement site, perpendicular to the tibial component. The distance from the tibial component to the bone surface was measured in millimeters (►**Fig. 3A**). Positive overhang measurements represent overhang where the component projects out

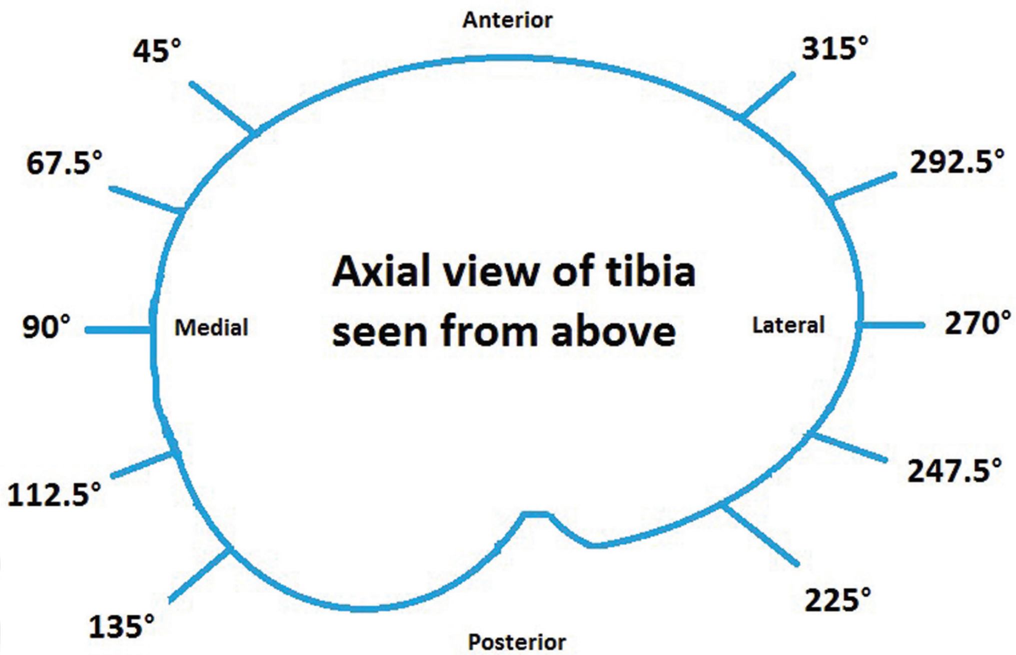

Fig. 2 Represents axial view of tibia from above, showing the 5 to 10 sites of measurement for unicompartmental knee replacement and total knee replacement, respectively.

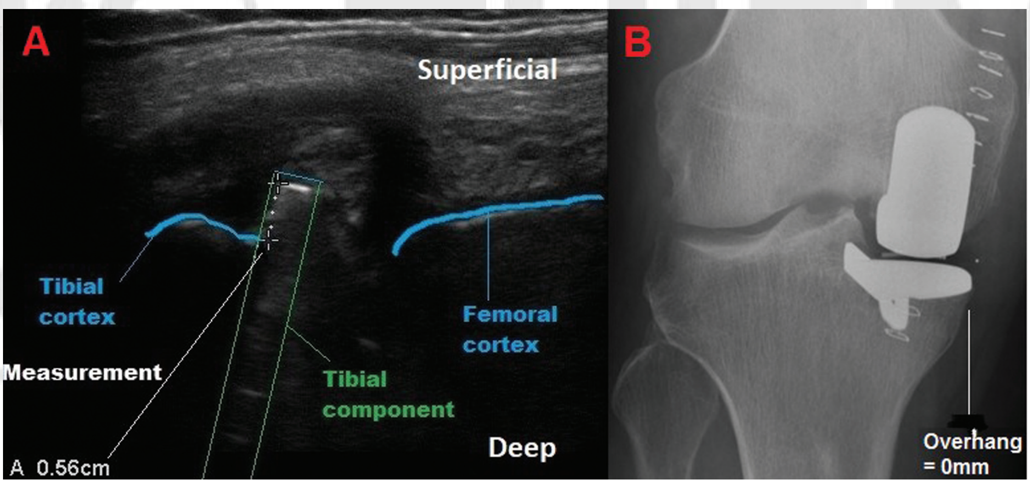

Fig. 3 (A) Ultrasound measurement perpendicular to the tibial cortex, at 112.5 degrees posteromedial, where blue is seen as the bone cortex, green as the tibial component, and the measurement of the drop shadow between the tibial component and the tibial cortex, represents the measurement of the overhang. (B) Radiograph of the same patient as seen in Fig. A. No overhang is seen medially on the radiograph, but is clear in Fig. A with ultrasound. Rotation of the tibia on the radiograph, which is a variation in postoperative radiographs, can create uncertainty of the extent of overhang.

over the bone surface, and negative numbers represent recessed components, that is, not reaching the bone margin. For each patient, the position of the maximal overhang was recorded. The reliability of the US was assessed by performing blinded double measurements on 15 patients, using two independent raters.

Conventional Radiology

The overhang was measured medially and laterally on conventional postoperative radiographs (►**Fig. 3B**). Radiographs of TKRs were performed supine directly after surgery. UKRs were performed postoperatively at 2 weeks, standing upright with full knee extension. The spherical stem in TKR's was used for calibration. Only in UKRs, the tibial baseplate or the femur shield in the anteroposterior view was used for calibration. In UKRs, this could potentially cause a slight inaccuracy, estimated at $\pm$ 0.1 mm, which we accepted.

Local Tenderness

A validated self-assembly pressure algometer was used to measure local tenderness as a PPT[20,23] by recording the amount of pressure required to elicit a sensation of pain distinct from a feeling of pressure or discomfort. Patients were asked to say "STOP" when a sensation of pain occurred during measurement.[21] The measurement in kg/cm^2 was recorded, and the algometer immediately released. A steady rate of pressure was applied, $\sim$0.5kg/cm^2 per second, until the PPT was reached.[19] Measurements at all of the sites were recorded. For comparison, 4 kg/cm^2 is enough pressure to whiten the nail bed of the fingertips of the examiner when performing palpation.[24]

Subjectivism of the perception of pain is known to vary depending on sex, age, anxiety level, and anticipation of pain.[19] To account for this subjectivism, we considered the mean of measurements at sites with no overhang to be the best expression of each patient's baseline tenderness. To determine whether the magnitude of overhang influences the local tenderness, we assessed the difference between the PPT at the maximum overhang and the mean PPT at sites with no overhang. We considered this difference to represent a local tenderness value: ΔLocal tenderness. A high value of ΔLocal tenderness indicates a high level of tenderness, and a low ΔLocal tenderness value is indicating low tenderness.

Statistics

An equality power-analysis comparing two proportions was performed. From the current literature, we found that the prevalence of overhang of more than 1 to 3 mm varies from 10 to 60%.[2,10–12] This finding allowed for reasonable assumption that our population would present with/without an overhang, with a ratio of 1:1. We assumed that 50% of the patients with overhang would present with local knee tenderness, while only 25% of patients without overhang would present with equal local tenderness. Power was set to 0.8 with a confidence interval (CI) of 95%. By this calculation, 55 patients should be included, and to allow for buffering, 64 participants were included in total.[25]

Patient demographics were compared with parametric statistics using independent *t*-tests. To rule out a possible sample bias, each surgeon's total operative activity during the inclusion period was compared with the number of patients operated by each surgeon in this study, using Fisher's exact test. Subgroup analysis was performed with the Wilcoxon signed-rank test. Tests of normality were performed using the Kolmogorov–Smirnov test. Associations were investigated using Pearson Correlation. Intraclass correlation coefficient was calculated to assess reliability of the US method. SPSS statistical package version 22 (IBM SPSS Inc, Chicago, IL) was used.

Results

The average patient age was 69.8 years (standard deviation [SD] = 8.1) with no difference between sexes ($p = 1$) and implant types ($p = 0.2$). The average body mass index (BMI) was 29.0 kg/m^2 (SD = 4) with no difference between sexes ($p = 0.1$) or implant types ($p = 1$). UKR and TKR patients had an US-determined overhang of more than 2 mm in 56 and 53% of cases, respectively, and overhang was most common posteromedially (►**Table 1**). The mean follow-up was 97 days postoperatively. The total operative activity of the surgeons at the high-volume center during the inclusion period was compared with each surgeon's activity in this study, showing no significant difference $p = 0.167$ between the groups.

A total of 94 measurements were included in the reliability analysis of double measurements. These measurements showed an intraclass correlation coefficient of 0.89 for all measurements, which can be categorized as good reliability, with excellent reliability being categorized for 0.9 and above.[26] Medial measurements showed an intraclass correlation coefficient of 0.88 (CI = 0.8–1; $p < 0.001$), and laterally 0.83 (CI = 0.6–1; $p < 0.001$), both indicating good reliability. Bland–Altman plots are seen with acceptable limits of agreement, and a mean difference close to zero, indicating similar measurements.

Radiographic measurements of medial and lateral overhang were compared with US measured overhang. The medial overhang is systematically underestimated by conventional radiography when compared with US. The rotational projection phenomenon is demonstrated by most points lying on or above the diagonal line, showing an underdiagnosed overhang in 61 out of 63 patients (►**Fig. 4A**). A mean difference of 2.4mm (CI: 2–3; $p < 0.001$) is seen between radiographs and US. On the lateral side of the knee, radiographs underestimated 22 out of 31 patients' overhang (►**Fig. 4B**). Here, a mean difference of 0.5 mm is seen, which is nonsignificant at $p = 0.2$.

Table 1 (Upper) Incidence of overhang size with US and radiographs, (lower) and location of the overhang (with US) above 2 mm per UKR/TKR, given in percentages

Overhang per prosthesis (%)	≥0 mm	≥1 mm	≥2 mm	≥3 mm	≥4 mm	≥5 mm
UKR ($n = 32$) with US	100	78.1	56.3	40.6	15.6	6.3
TKR ($n = 32$) with US	78.1	71.9	53.1	28.1	12.5	9.4
UKR ($n = 32$) with radiographs	11	9.4	4.7	0	0	0
TKR ($n = 32$) with radiographs	40.7	26.6	11	4.7	1.6	0
Incidence per location with US (%)	**AM**	**M**	**PM**	**AL**	**L**	**PL**
UKR ($n = 17$)	29.4	11.8	58.8	–	–	–
TKR ($n = 18$)	0	16.7	55.6	0	11.1	16.7

Abbreviations: AL, anterolateral; AM, anteromedial; L, lateral; M, medial; PL, posterolateral; PM, posteromedial; TKR, total knee replacement; UKR, unicompartmental knee replacement; US, ultrasound.
AL = 225–247.5 degrees; L = 270 degrees; PL = 292.5–315 degrees
AM = 45–57.5 degrees; M = 90 degrees; PM = 112.5–135 degrees.

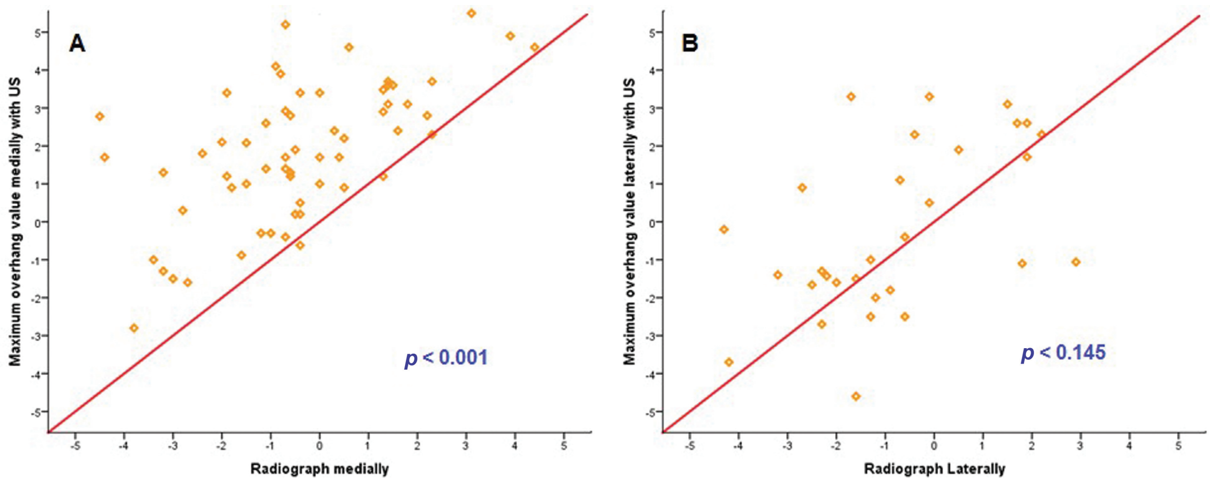

Fig. 4 Scatterplots of radiographs versus ultrasound medially and laterally, respectively. Circles seen above the red diagonal line represent a rotational projection phenomenon of radiographs, and circles on the line represent equal measurements between radiographs and ultrasound.

The mean difference in pressure pain tenderness between the mean of sites with no overhang and the site with maximal overhang, that is, ΔLocal tenderness, was 1.3 kg/cm^2 (CI: 1–2; $p = 0.001$) signifying significantly more tenderness at the site with maximal overhang.

A positive linear Pearson correlation was found between patients' ΔLocal tenderness and overhang ($r = 0.25$; CI = 0.02–0.5; $p = 0.045$). A significantly higher mean difference in ΔLocal tenderness of 3.2 kg/cm^2 (CI: 1–6; $p = 0.01$) was found in the TKR group compared with the UKR group. No difference was observed between males and females.

The following subgroup analyses consisted of patients having ≥2mm overhang. ΔLocal tenderness was compared between medial overhang patients (position 90 degrees, $n = 5$) and patients with overhang in all other locations ($n = 30$), demonstrating a significantly higher ΔLocal tenderness for patients with maximal overhang directly medially compared with other locations of the maximal overhang with a median difference of 6.7kg/cm^2 (CI: 2–11; $p = 0.008$). Patients with medial maximal overhang compared with patients with posteromedial maximal overhang ($n = 20$), demonstrated a significantly higher ΔLocal tenderness medially (median difference 6.4kg/cm^2; CI: 2–11; $p = 0.04$). Comparing patients with posteromedial overhang to all other locations proved nonsignificant ($p = 1$). These three subgroup analyses are presented visually in ►**Fig. 5**. No significant difference was found when comparing lateral maximal overhang patients to patients with maximal overhang in all other locations ($p = 0.6$)

Discussion

US is becoming increasingly popular for visualizing bone surfaces, and more advanced techniques with US are becoming available, as mentioned in a newly scoped review on the subject.[17] US is not considered the gold standard to analyze components and bone dimensions. Still, our study has shown good reliability of this method, even though state-of-the-art US technology was not used. The bone surface of the tibia and the metal component are quickly found with a standard US-probe, allowing for instant and precise depth-measurement of the drop shadow between these large and prominent structures, thereby assessing the overhang (►**Fig. 3A**). This highlights how relatively cheap, easy-to-use, portable, and precise equipment can be used to quickly assess tibial component overhang.

Radiographs versus US

US is a relevant tool for investigating medial and especially posteromedial overhang if this is suspected. When comparing radiographs and US, we detected a significant difference medially, but not laterally. Two patients had an overhang measured laterally on radiographs while measuring a negative overhang with US. These results cast doubt on the usefulness of US when measuring laterally.

Optimal postoperative radiography should be done with guidance from fluoroscopy,[27,28] but this is not always feasible. Oblique radiographic views are also a possibility but impose additional costs and cause more radiation. Metal artifact reduction in computed tomography (CT) or magnetic resonance imaging (MRI) are also good alternatives for avoiding the rotational projection phenomenon, but are not always available, and are also more costly and cause more radiation than radiographs.

It could be argued that the polyethylene, in cases with the Oxford mobile-bearing prosthesis, could cause an even larger antero- or posteromedial overhang, but it does not seem to have any significance medially.[29]

Prevalence, Incidence, and Size of Overhang

The literature is inconsistent on the prevalence, incidence, and size of overhang. Some studies classified overhang as being "minor" if under 3 mm, and "major" overhang if over 3 mm.[2,11] Overhang has been classified as excessive, if above 2 mm,[12] which corresponds to Zimmer Biomet's surgical technique handbook for medial UKR.[12,13] The incidences of overhang vary widely, likely because of a lack of consensus regarding the definition of overhang. One study measured overhang on TKRs dichotomously demonstrating that medial

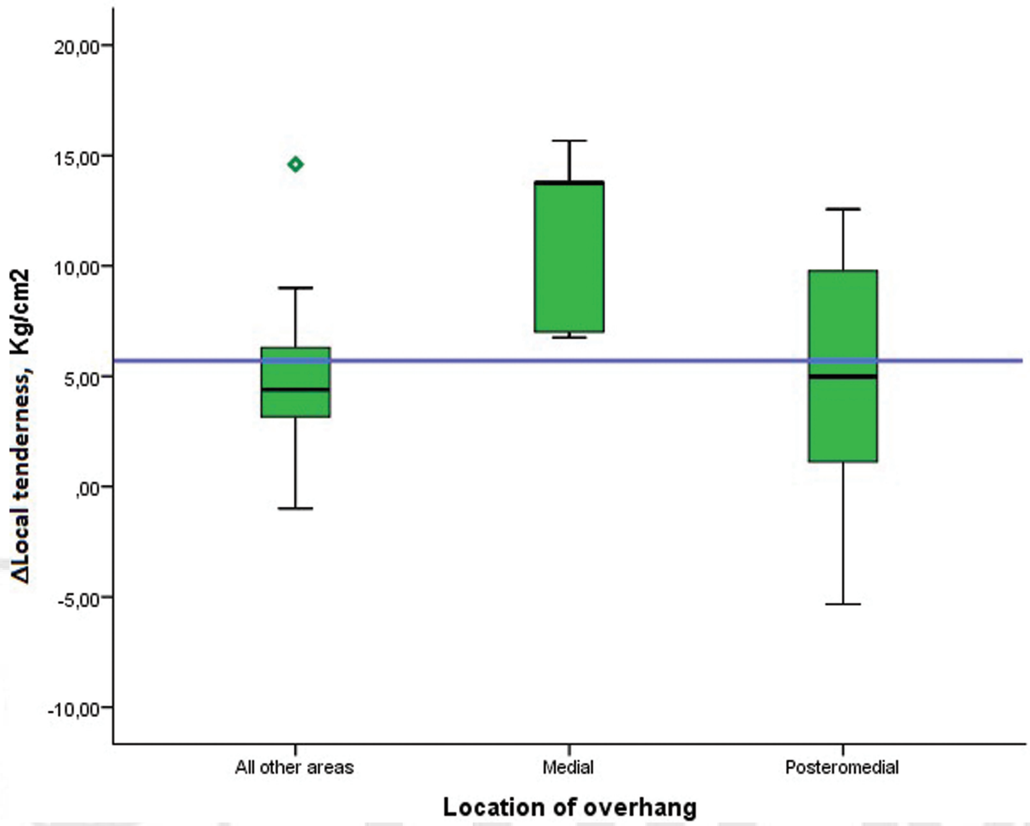

Fig. 5 Boxplots visualizing subgroup analysis of patients with an overhang of ≥2mm, and their respective location. The blue line represents the median across all groups.

overhang was measured in 18.0% and lateral overhang in 32.2% patients.[10] Another study of TKRs found that 60% had overhang under 3 mm, and 9% had over 3 mm.[2] In a study of UKRs, 10% had an excessive overhang over 2 mm.[12] Our study presents an incidence of 53 to 56% of overhang over 2 mm, 28 to 40% of overhang over 3 mm, and 12 to 15% over 4 mm. When comparing these incidences of overhang with US to the incidences of overhang found on radiographs (►**Table 1**), this could reflect the underreporting observed in the literature, possibly explained by the rotational projection phenomenon when only using radiographs.

Choice of implant and the presence of malrotation also influence the presence and incidence of overhang. If using symmetrical tibial components in TKA, a study showed lateral overhang in 42% compared with 3% with an asymmetrical component. The presence of internal malrotation resulted in 6% incidence of overhang for the symmetric components, and 71% for asymmetric design.[30]

Other risk factors such as age, BMI, ethnicity, and gender have also been proven to affect proximal tibial morphology, and as such will not necessarily be equally applicable to standardized tibial baseplates.[31,32]

Local Tenderness

In this study, we found a positive albeit poor correlation between overhang and patients' local tenderness level, regardless of the location of the overhang. Our subgroup analysis results of medial overhang and its association with a higher ΔLocal tenderness are similar to previous findings.[10] Worse outcomes are seen with the presence of medial overhang, and no difference in outcome if a lateral overhang is present. These results could be explained by the close anatomical location of the medial collateral ligament (MCL) to the tibial component compared with the lateral collateral ligament. Another study investigated the effect of posterolateral overhang, finding worse Knee Society scores.[33] The same study found significant differences in groups with and without posterolateral pain, showing a mean of 3.6 and 0.02 mm overhang, respectively.[33] In this study, the most frequent location of the overhang was posteromedial (►**Table 1**). Yet, findings suggest that a posteromedial overhang is not a leading cause of local tenderness and is perhaps more forgiving.

A cadaver study of medial UKRs showed that when overhang increased from 2 to 4 mm, MCL loading doubled. The study argued that increased MCL loading might lead to pain or tenderness. Therefore, the authors recommended that overhang above 2 mm should be avoided in medial UKRs,[5] which is consistent with our findings.

Limitations

A limitation of our study is the lack of measurements of overhang of the femoral component, which theoretically also may cause tenderness medially. Anterior and posterior measurements were not considered since medial and lateral tissues were of particular interest, and since soft tissues posteriorly made PPT measurements uncertain. The conventional radiography of UKRs was not calibrated with a spherical object, but the study group found the margin of error to be acceptable. US is operator dependent, and measurements of this type have not been presented in the literature.

Measurements of local tenderness can be argued to be nonspecific, because of ongoing active inflammation in the knee postoperatively. However, this study's results still show statistically significant differences in sites with overhang compared with sites without overhang.

The significance of lateral overhang could be more considerable than found in this cohort since half of the included participants in this cohort have a medial UKR. An earlier study has proven similar findings laterally, as this study has found medially.[33] Therefore, conclusions on the effect of lateral overhang from this study should not be considered conclusive.

A previous failure analysis of TKRs demonstrated that in a subgroup of mechanical failures, ~7% was attributed to overhang.[3] A study of failed UKRs found that "surgical errors were present in 50% of failed UKR's, with most errors attributable to tibial component placement and orientation"[34]. Higher incidences of overhang have been presented in our study compared with previous studies. Moreover, a correlation to increased local tenderness has also been shown. These findings could raise the question, whether overhang is attributable to a more considerable number of revisions than presented in the literature. Our findings highlight the importance of awareness of component positioning perioperatively, and the importance of using diagnostic tools to visualize the components in more than two-dimensional when patients present with knee pain and tenderness. Future studies of overhang should optimally include diagnostic tools allowing 360 degrees visualization of the tibial component, such as US or MAR-CT/MAR-MRI and should include clinical assessments of pain and relevant patient reported outcomes for a longer follow-up. One new study has investigated tibial overhang with a rotational CT protocol, allowing assessment of total percentage of overhang of the tibial component, showing correlation ($r = 0.23$, categorized as negligible correlation $r = 0.00–0.3$[35]) increased overhang with five points decreased Knee injury and Osteoarthritis Outcome Score (KOOS) at 1 year follow-up.[36] Optimally, the precise location and local size of the overhang should be assessed including a clinical evaluation of tenderness at the same sites, supported with patient reported outcomes at these follow-ups over a longer period.

Conclusions

This study showed US to be a reliable tool to determine tibial component overhang of both UKR and TKR. A positive linear correlation was found between overhang and local tenderness suggesting overhang to result in a higher local tenderness when located medially in relation to the MCL. These findings encourage awareness of implant type and size and positioning during surgery, and the use of US to detect possible tibial component overhang in clinical practice.

Ethical Approval

The Danish Ethics committee did not deem this study necessary for ethics approval, as there was no radiation and intervention to the participants. Participants gave informed consent.

Conflict of Interest

None declared.

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