11-28-2022 4:30 PM

Comparison of Hip Navigation System Accuracy in Direct Anterior Approach

Jeremy Loh, *The University of Western Ontario*

Supervisor: Lanting, Brent, *The University of Western Ontario*
: Howard, James Layton., *The University of Western Ontario*
: Teeter, Mathew G., *The University of Western Ontario*

A thesis submitted in partial fulfillment of the requirements for the Master of Clinical Science degree in Surgery

Abstract

Introduction

Malposition of the acetabular component has been thought to have an influence on increasing increase the risk instability, impingement, and ultimately revision surgery. Hip navigation technology has been developed to provide the surgeon with real time intraoperative metrics to make critical decisions in implant placement. The goal of this study was to compare the accuracy of acetabular component positioning in direct anterior approach hip replacements using conventional fluoroscopy only technique, fluoroscopic image dependent navigation, and imageless navigation.

Methods

A retrospective data collection and prospective analysis was conducted for this study. After sample size calculations, fifty patients were collected for each group for analysis. Intraoperative cup inclination and anteversion was collected for all three groups. Post-operative AP radiographs at six weeks post-surgery were analysed in all three cohorts to determine final inclination and anteversion. Two readers conducted radiographic analysis. The primary outcomes for the study included: absolute deviation from intraoperative and post operative anteversion/inclination, absolute mean deviation from surgeon's target zone, and number of cups within target zone. Secondary outcomes included operative time and 60-day complications (dislocation, infections, periprosthetic fracture). In previous literature, the use Lewinnek's safe zone has been utilised as the ideal target for acetabular component position. In our study, we used specific surgeon's preference for the target zone. Surgeon A had a target zone of inclination 40^{O} +/- 5^{O} and anteversion 20^{O} +/- 5^{O}. Surgeon B had a target zone of inclination 35^{O} +/- 5^{O} and anteversion 15^{O} +/- 5^{O}.

Results

The inter-rater reliability demonstrated good agreement for radiographic analysis between observers for inclination (ICC = 0.855 (n=200)) and anteversion (ICC = 0.894 (n=200)). Our study analysed the absolute deviation of cup position determined by 6-week post-operative radiographs from target position, the mid-point of each surgeon's specific safe zone. This variation was defined as placement error. There was no significant regarding final cup position from desired targets of anteversion (P=0.08) and inclination (P=0.94) when comparing all three groups. Our study also looked at intraoperative versus post operative cup positioning accuracy known as estimated error. Conventional fluoroscopic use demonstrated statistically significant inaccuracy in inclination and anteversion (P<0.0001). Imageless navigation demonstrated significant inaccuracy in anteversion (P=0.00043).

In terms of final cup positioning, Surgeon A achieved 59% (16/27 cups) within the specific target while Surgeon B obtained 48% (11/23 cups) when using conventional fluoroscopy only. With the use of image guided navigation, VELYS, Surgeon A achieved 83% (20/24 cups) while Surgeon B obtained 69% (18/26 cups) within their defined zones. With the use of imageless navigation, Surgeon A had 76% (20/26 cups) while Surgeon B had 50% (12/24 cups) within target zone.

Imageless navigation demonstrated increase length of operative time in comparison to VELYS and fluoroscopy only group on average with 75.5 mins (P<0.0001). There was no difference in complication rates across all three groups at 60 days follow-up.

Conclusion

Our study found that in comparison to conventional fluoroscopy, hip navigation allowed for more accurate placement of cups. Image guided navigation demonstrated significant estimated error in evaluation of cup anteversion. We found that operative time was increased when using imageless navigation.

Keywords
Total Hip replacement, Navigation, Direct Anterior Approach

Lay Summary

Malposition of the acetabular component has been thought to have an influence on increasing the risk instability, impingement, and ultimately revision surgery. Hip navigation technology has been developed to provide the surgeon with real time intraoperative metrics to make critical decisions in implant placement. The standard use of intraoperative fluoroscopy has been adopted to aid the surgeon in component placement in the direct anterior approach. At our institution, we utilise two hip navigation systems in direct anterior hip replacements. The image guided navigation system relies on intraoperative fluoroscopic imaging to create a digital map for intraoperative implant positioning. The imageless navigation system relies on intraoperative kinetic data points of anatomical landmarks to provide real-time component position parameters.

The goal of this study was to compare the accuracy of component positioning in direct anterior approach hip replacements using conventional fluoroscopy only technique, fluoroscopic image dependent navigation, and imageless navigation. This was achieved by comparing intraoperative measurements of acetabular component position with postoperative radiographic measurements.

Our study found that in comparison to conventional fluoroscopy, the use of hip navigation technology allowed for more accurate placement of acetabular components. Image guided navigation demonstrated significant estimated error in evaluation of cup anteversion. We found that operative time was increased when using imageless navigation.

Keywords
Total Hip replacement, Navigation, Direct Anterior Approach

Co-Authorship Statement

This retrospective study was designed in collaboration with Dr. Lanting, Howard, and Teeter. I was responsible for conducting the study including patient identification, data collection and data analysis. I wrote the original draft of this thesis document. Dr. Lanting and Dr. Howard made comments and suggestions towards the final submission.

Acknowledgments

I would like to thank my co-supervisors, Dr. Brent Lanting, Dr. James Howard, and Dr. Matthew Teeter. Their constant support, patient and guidance has meant a lot to me throughout my Master's at Western University. I would like to thank Dr. Eoghan Pomeroy for his assistance in radiographic analysis. I would also like to thank Louis Charron for assisting with statistical analysis.

Table of Contents

List of Tables

List of Figures

List of Appendices

Acronyms

OA - Osteoarthritis

DAA – Direct Anterior Approach

THA – Total Hip Arthroplasty

AP – Anterior posterior

APP - Anterior Pelvic Plane

ASIS – Anterior Superior Iliac Spine

QALY – Quality Adjusted Life Years

DRF – Dynamic Reference Frame

LLD – Leg Length Discrepancy

CT – Computed Tomography

PACS - Picture Archiving and Communications System

RSA – Radiostereometric Analysis

Chapter 1

1 Study Summary, Purpose and Hypothesis

In 2020-2021, there were 55,300 hips replaced in Canada according to registry data. It is estimated that there will be an increase of 172% in demand for hip arthroplasty over the next decade. [1] The direct anterior approach has also seen a rise in popularity with enthusiasm for potential faster early recovery, reduction of pain, and lower instability with preservation of soft tissue.

Malposition of the acetabular component has been thought to possibly increase the risk of instability, impingement, wear, and ultimately revision surgery. The supine patient position in the direct anterior approach allows for the use of fluoroscopy as an intraoperative tool to provide real time component position. Hip navigation technology has also been developed to provide the surgeon with real time intraoperative metrics to make critical decisions in implant placement.

At our institution, we utilise two hip navigation systems in direct anterior hip replacements. The VELYS™ navigation system (Depuy, Warsaw, IN) relies on intraoperative fluoroscopic imaging to create a digital map for intraoperative implant positioning. The INTELLIJOINT® navigation system (INTELLIJOINT® Surgical, Inc, Waterloo, ON, Canada) is an imageless system that relies on intraoperative kinetic data points of anatomical landmarks to provide real-time component position parameters.

The goal of this study was to compare the accuracy of component positioning in direct anterior approach hip replacements using conventional fluoroscopic technique, fluoroscopic image-dependent navigation, and imageless navigation. This was achieved by comparing intraoperative measurements of acetabular component position with postoperative radiographic measurements. We hypothesized that the two navigation systems would demonstrate improved accuracy in comparison to conventional technique. When comparing VELYS™ and INTELLIJOINT®

navigation accuracy, we predicted that they will be equivalent in accuracy of component positioning.

Chapter 2

2 Literature Review

2.1 Hip Anatomy

The hip joint is a synovial joint made up of the femoral head and acetabulum as the main components. [2] The anatomy is depicted in Figure 1. The joint itself experiences forces up to five times body weight during running and climbing stairs. [3]

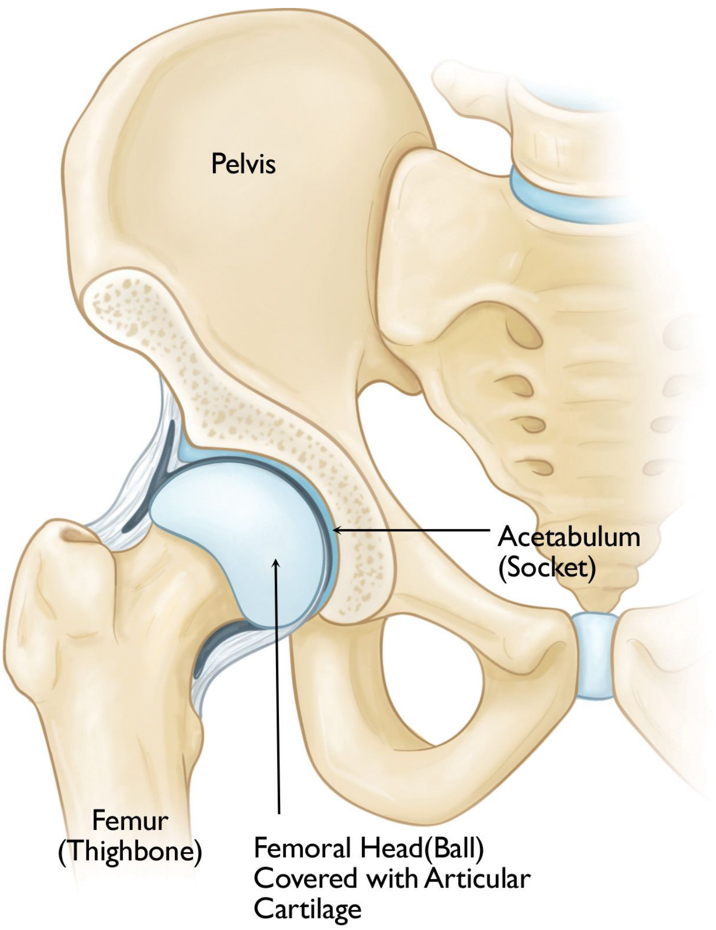

Figure 1: Anatomy of the Hip
(Reproduced with permission from OrthoInfo. © American Academy of Orthopaedic Surgeons. https://orthoinfo.org/)

Soft tissue structures such as the labrum, ligaments and musculature help to support the joint. The two articulating surfaces of the hip joint are lined by hyaline cartilage. The hyaline cartilage is made up of chondrocytes interspersed in extracellular matrix, which is comprised of proteoglycans. Aggrecan and Type II collagen are predominantly found in the matrix, providing the major scaffolding of cartilage. The negatively charged glycoprotein gives cartilage its viscoelastic properties. Nutrition to the cartilage is provided by diffusion through the matrix. [2]

The acetabular architecture is composed of three ossification centres: the ilium, ischium, and pubis. The anterior, posterior and dome of the acetabulum originate from the combination of the three ossification centres. Fibrocartilage lines the outer perimeter while hyaline cartilage compromises the weight bearing portion of the acetabulum. The weight bearing cartilage forms a horseshoe shaped distribution with the acetabular fossa central to this. [4] The acetabular fossa contains the ligamentum teres and pulvinar at the floor of the acetabulum. The ligamentum serves as an attachment to the femoral head fovea. The labrum, comprised of fibrocartilage over the outer edge of acetabulum, helps to deepen the socket and to distribute forces seen at the joint. The transverse acetabular ligament has as its main role to form a tension band between the anterior and posterior wall, also serving as a landmark for total hip implant positioning. The anterior and posterior columns help to support the acetabulum, providing a foundation for force transmission. [3]

At the age of 14-16, the triradiate cartilage is fully ossified leading to 170 degrees of concentric femoral head coverage. The average diameter of an adult acetabulum is 52 +/- 4mm. The mean anteversion of the native acetabulum is between 16-21 degrees and a mean inclination of 48^{O}. Males tend to have a smaller magnitude of anteversion. [3]

The bony anatomy of the proximal femur is made up of the femoral head, neck, greater and lesser trochanter. The average anteversion of femoral neck is 10.5+/- 9.22 degrees. [3] The average neck-shaft angle is around 125 degrees. The greater trochanter serves as the insertion point of the abductor muscle complex, gluteus medius and minimus. The lesser trochanter is posteromedially positioned with a retroverted position of 31.5 degrees. The iliopsoas tendon inserts on to the lesser trochanter. [4]

The hip capsule is comprised of the iliofemoral, ischiofemoral and pubofemoral ligaments. The inner aspect of the capsule is made up of the circumferential zona orbicularis layer fibers. The capsule serves as a network of structures for stability of the hip joint and to provide nutrients, blood supply to the joint. The capsule spans from the lateral border of the acetabulum to the intertrochanteric area of the proximal femur. Besides the capsular structures that provide the static stability of the hip, the muscles surrounding also provide dynamic stability. The hip is surrounded with the flexor compartment anteriorly, extensor muscles posteriorly and the abductor complex including the tensor fascia lata laterally. The adductor muscles can be found on the medial aspect of the joint. The external and internal hip rotators also provide stability around the hip joint. [3]

2.2 Osteoarthritis

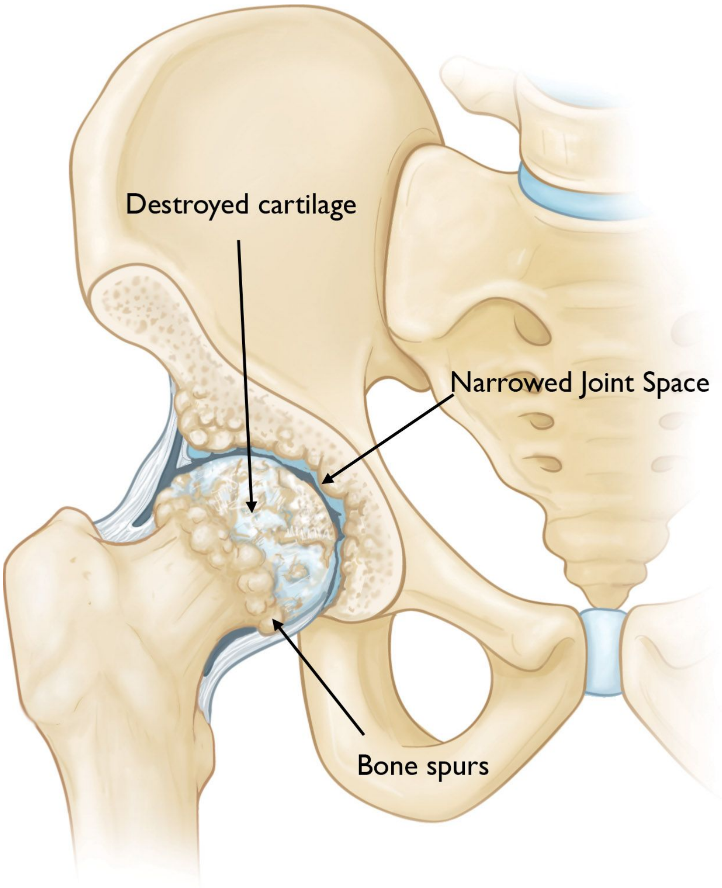

Figure 2: Osteoarthritis of the hip
(Reproduced with permission from OrthoInfo. © American Academy of Orthopaedic Surgeons. https://orthoinfo.org/)

The definition of osteoarthritis (OA) is a disease process that initially begins with molecular derangement, abnormal joint tissue metabolism leading to subsequent anatomic derangement. Physiologic changes lead to cartilage degradation, bone remodelling, osteophytes formation, joint inflammation, and loss of normal joint destruction. Osteoarthritis is the most common joint affecting disease worldwide. It is characterized by cartilage degeneration and subsequent joint destruction. The major risk factors implicated are age, female sex, obesity, genetics and previous joint trauma. [5]

It has been found the osteoarthritis leads to decreased physical activity amounting to a 20% higher age-adjusted mortality for patients. The financial implication of income losses due to OA has been estimated at $65 billion and medical financial burden exceeding $100 billion. [5] Patients diagnosed with OA have 10-25 % lower quality of life in comparison to control population. [6]

There appears to be an increasing prevalence of radiographic OA with aging in both men and woman. Men demonstrate a high prevalence of hip OA before the age of 50, while women demonstrate higher prevalence after the age of 50. This difference in prevalence based upon sex is thought to be attributed to hormonal protective factors. [2] There is a 25% lifetime risk of symptomatic hip osteoarthritis in patient's aged 85 with a 10% lifetime risk of requiring a total hip replacement. [7] Caucasian populations have 3-6% prevalence of hip osteoarthritis in comparison to less than 1% in Asian and African populations. [2]

A healthy joint normally experiences physiological biomechanical loading, which helps to maintain a homeostatic equilibrium between joint tissue degradation and repair. Several factors at the cellular and molecular level are released as result of abnormal joint shear stress. This stress leads to increasing expression of proinflammatory cytokines and subsequent apoptotic cellular damage in OA. [7]

Several proinflammatory cytokines like interleukin 6, monocyte chemoattractant protein 1 have been implicated in contributing to osteoarthritis. These proinflammatory cytokines are responsible for stimulation of matrix-degrading enzymes like metalloproteinases. [5] These proteases lead to degradation of aggrecan and collagen framework in cartilage. [2] There is an overall imbalance in the catabolic and anabolic factors influencing joint health, with proinflammatory factors causing tissue degradation more rapidly than tissue repair can occur. [5] The combination of biomechanical and biochemical factors leads to imbalance between damage and repair of tissue. Swelling, decreased tissue compliance, fracturing and fibrillation leads to destruction of cartilage with subsequent eburnation of the underlying subchondral bone. The subchondral bone and articular cartilage behave as a functioning unit in a healthy joint. The abnormal forces lead to cartilage microcracks that affect the non-calcified, tidemark and calcified cartilage regions. Fissuring of these layers leads to neovascularization and passageways for cytokines to damage and create remodelling of the underlying subchondral bone. [7] The tissue reparative process creates Type 3 collagen forming fibrocartilage. This tissue unfortunately lacks the same unique characteristics of hyaline cartilage of compliance and shock absorbance. [2]

Synovitis found in osteoarthritis has been attributed to macrophage activity in comparison to rheumatoid disease where T cell activity is the underlying mechanism. [5] The pathophysiology of OA is a constellation of biological process that involves the cartilage, bone, synovium, ligaments, periarticular fat, meniscus, and muscle. The radiographic findings are characterized by loss of joint space due to cartilage wear, sclerosis of the subchondral bone, and cyst and osteophyte formation. [5]

Osteoarthritis is classified as primary or secondary. In primary OA, the cause is unknown however its thought to be contributing of genetic factors, aging of chondrocytes, mechanical factors (wear and tear) and biochemical factors. A twin study reported 60% risk for hip OA attributed to genetic factors. [8] In secondary OA, there is a predisposing risk factor such as posttraumatic, mechanical incongruity (congenital versus traumatic), previous inflammatory joint disease (septic joint), blood dyscrasia, neuropathic joint, endocrinopathies or repeated steroid injections. [2] Risk factors for hip OA can be subdivided into joint level and patient level risk factors. Joint level risk factors include abnormal joint morphology such hip dysplasia or femoral acetabular impingement. Patient level factors include age, sex, weight, ethnicity, occupation, and genetics. A five-point increase in BMI is linked with an 11% increased risk of hip osteoarthritis. [7]

Patients with hip arthritis suffer from pain as the primary symptom. This is usually characterized by a dull ache with catching symptoms in the groin and lateral aspect of the hip. The pain is thought also to be generated by the periosteal reaction, interosseous congestion, synovitis, and surrounding muscular contractures. More than 50% of patients have hip pain, which can radiate to their knee as a primary complaint. Stiffness, crepitus, and gait disturbance are other symptoms experienced with an osteoarthritic hip. Hip arthritis leads to impairment of mobility, loss of independence and increased health service demand. [8]

The diagnosis of hip OA is based upon the history and physical examination of the patient, in conjunction with plain radiograph imaging of the hip. The physical examination includes inspection of leg lengths, deformity, gait, neurovascular exam, and joint range of motion evaluation. The Lawrence Kellgren classification for OA of hip is defined as four parameters: 1) osteophytes at the joint margins 2) narrowing of articular cartilage with sclerosis of subchondral bone 3) subchondral cysts 4) remodelling of femoral head. [2] Osteoarthritic changes are depicted in Figure 2. Patient reported outcomes like the Oxford Hip scores have been utilised to assess disease progression. There is a discrepancy between symptoms experienced and radiographic findings in a portion of patients with hip osteoarthritis. [7] Therefore it is important that history, physical examination, and radiographs are considered during formulation of the diagnosis.

2.3 Treatment of Hip OA

The initial steps of the treatment algorithm are primary prevention which involves lifestyle changes like weight reduction and activity modification. [7] The aim of weight reduction to reduce the forces and subsequent joint impact is especially important. Increasing one's weight by ten pounds leads to an increase of sixty pounds of pressure experienced at the hip joint with each step. There are number of nonpharmacological treatment modalities having been recommended for the management of symptomatic hip arthritis. The focus of physical therapy, which includes aquatic based activities, is to strengthen periarticular musculature to ease hip pain. [8]

The use of oral analgesics has been explored in non-operative management of joint arthritis. Acetaminophen in comparison to NSAIDS (Non-Steroidal Anti-Inflammatory Drugs) has been shown to have less of an effect in the hip. Diclofenac and etoricoxib have been shown to be most effective in pain relief of hip OA. [8] Intra-articular injections in the hip joint are variable in reported therapeutic effect due to the anatomical challenges of accessing the joint. Corticosteroid infections have been shown to have no greater pain relief in comparison to placebo after 3 months follow up and potentially inferior to physical therapy at 1 year. [5] With therapies such as hyaluronic acid injections and platelet rich plasma injections, the evidence regarding efficacy as a treatment is still inconclusive. Regarding PRP (Platelet Rich Plasma) injections for treatment of hip OA, two studies conducted demonstrated conflicting conclusions with one demonstrating no difference while the other found efficacy at 2 and 6 month follow ups. [7]

2.3 Total Hip Replacement

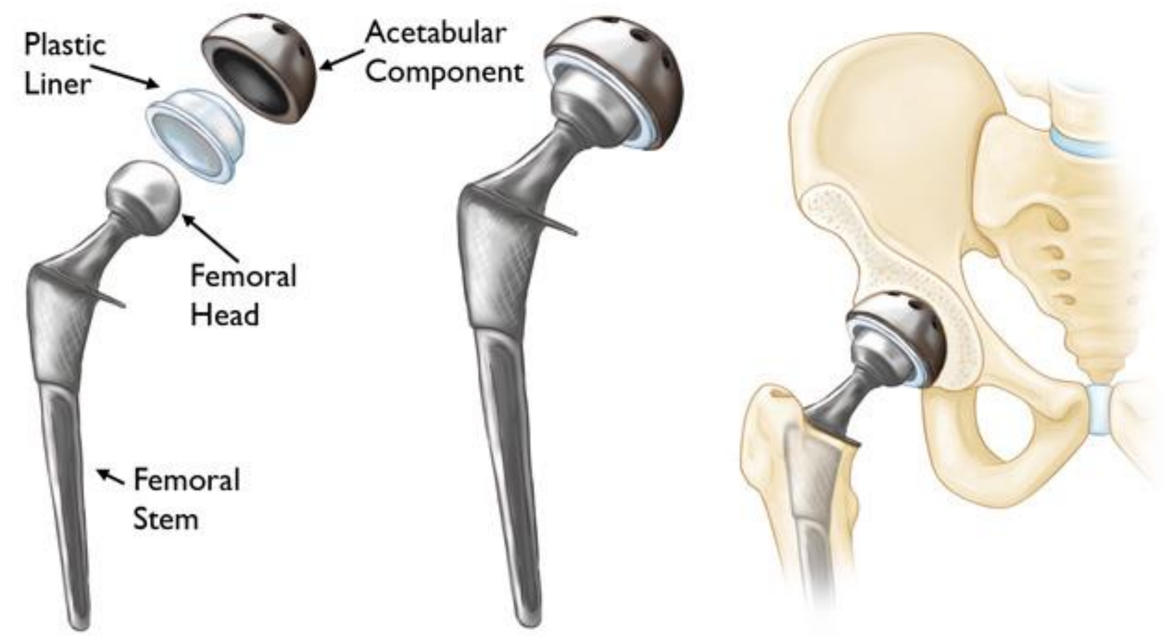

Figure 3. Total Hip Replacement

(Reproduced with permission from OrthoInfo. © American Academy of Orthopaedic Surgeons. https://orthoinfo.org/)

The mainstay of treatment for end stage arthritis of the hip joint is joint replacement when non-operative treatment has been fully exhausted. The first total hip was created by Wiles in 1938, but was not widely adopted until Sir John Charnley introduced his prosthesis for treatment of hip arthritis. [9] 330 000 Primary total hip replacements are performed annually in the US, with 90% of the surgical indication for OA. It is estimated that there will be a 172% increase in need for hip replacement surgery in the next ten years. [10] THA is a safe procedure, with 90-day mortality less than 1% and 90-day serious complications occurring less than 5%. 90% of patients having undergone a THA report little to no residual pain. [5] Laupacis et al found that in the first three years following total hip replacement, there was a $8731 per QALY (quality-adjusted life years) gained, leading to the conclusion that this procedure is highly cost effective in addition to its other merits.[11]

Other surgeries like arthrodesis or pelvic osteotomy have been utilised as alternatives to THA. Arthrodesis in the young arthritic patient was a popular surgical intervention due to previous concerns of hip replacement longevity. However, with improving survivorship in hip replacement surgery and higher patient dissatisfaction associated with arthrodesis; this procedure has fallen out of favour even in the young adult population. [12] With excellent survivorship of implants and high patient satisfaction, total hip replacement has become the gold standard treatment of end stage arthritis. Total hip replacement surgery, measured by validated health related outcome tools, has been shown to decrease hip pain, improve mobility and motor function in patients with end stage arthritis. [10] Total hip arthroplasty has been shown to have an associated health care cost saving of $278 per annum per patient operated versus patients who are non-operative and incur an increase of $1978 every year. [13]

Prior to Charnley's innovation, interposition graft and crude attempts at the modern total hip replacement were attempted. Fascia lata grafts and gold foil were among the trialled interposition layers inserted between acetabulum and femoral head to treat arthritis. Charnley was responsible for many factors that have led to the modern total hip replacement. Charnley’s concepts included the ideas of low frictional torque arthroplasty, hip biomechanics, materials, design, and fixation. [14]

The evolution of the modern total hip replacement has seen much advancement since Sir Charnley’s low frictional torque hip arthroplasty. Development of metallurgy, tribology and surgical techniques has led to improved survivorship of hip replacements. Cementation fixation techniques have slowly been modernized from the simple finger packing of the polymer to proper femoral preparation and pressurization to form a uniform cement mantle. The bearing surface, in particular introducing of highly cross-linked polyethylene has revolutionized wear properties and longevity of hip arthroplasty.

The modern total hip replacement consists of a femoral component, femoral head, acetabular shell and liner (Figure 3). There exist a variety of femoral stem designs with uncemented versus cemented fixation. The modern hip implants provide a degree of modularity with the femoral head and acetabular liner separate from the shell. [15] The most common bearing surfaces utilised in Canada are metal (cobalt-chrome) and highly cross-linked polyethylene with cementless acetabular and femoral component fixation. The main innovations in total hip replacement surgery have been targeted towards implant durability, reduction of wear regarding articulating components and technical adjustments to improve patient recovery and accuracy of implant positioning. [14]

The most common complications associated with total hip replacements can be categorized as intraoperative, early and late. Intraoperative complications include fracture, neurovascular injury, leg length discrepancy, malposition, and anaesthetic complications. Early complications include bleeding, periprosthetic infection, instability, and venous thromboembolism. Late complications include periprosthetic fracture, aseptic loosening and implant failure. [16]

2.4 Total Hip Implant Orientation

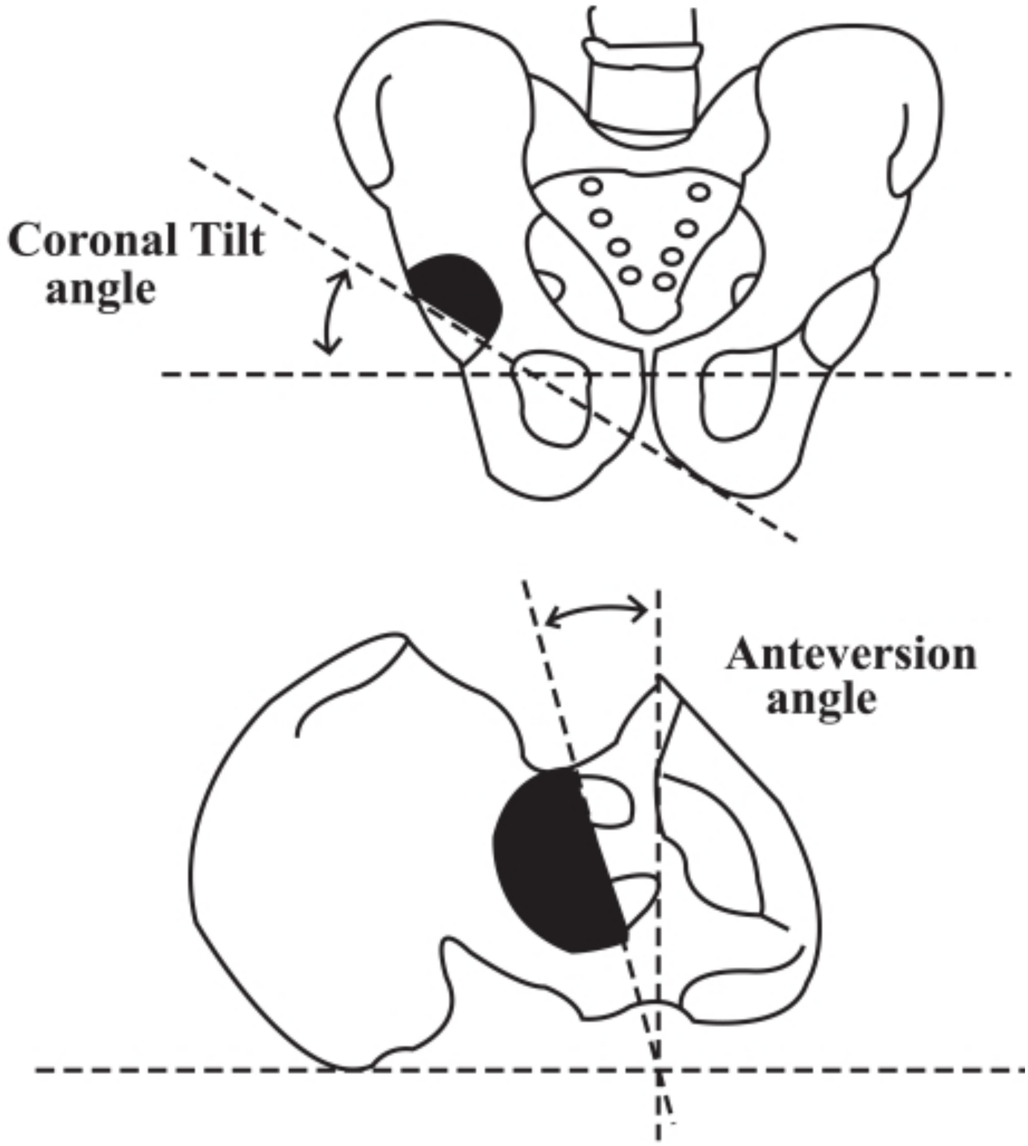

Figure 4. Diagram demonstrating Cup Inclination and Anteversion. (Reproduced with permission from Mirza et al. (2010). Basic science considerations in primary total hip replacement arthroplasty. *The open orthopaedics journal*, *4*, 169–180. https://doi.org/10.2174/1874325001004010169

The cup inclination is the angle between the longitudinal axis of body and the acetabular axis. The cup anteversion is defined by the angle between the acetabular axis and the coronal plane.[17] Inclination angle is measured between the face of the acetabular component and the horizontal axis drawn by connecting the intra-tear drop line. This is depicted in Figure 4.

The definition of combined anteversion refers to position of acetabular and femoral components within a safe zone of impingement free range of motion. [18] The safe zone to prevent dislocation has been described by several groups making a consensus target to be desired still. Barrack et al described an acceptable target of 45^{O} +/- 10^{O} abduction and 20^{O} +/- 10^{0} anteversion. Several studies have adopted Lewinnek et al described safe zone of 40^{O} +/- 10^{0} abduction and 15^{0} +/- 10^{0}. In a study done by Abdel et al., 58% of 206 dislocated hip replacements had components within the Lewinnek safe zone. [19] Barrack et al proposed anteversion of 10^{0} - 20^{0} for both cup and stem components. [20] Sendtner et al suggested combined anteversion of 25^{0} to 40^{0}, while Dorr et al proposed a target of 35^{0}, with range from 25^{0}-50^{0}. [21,22] A recent study by Hevesi et al found that the ideal modern safe zone lies within 27-47^{O} inclination and 18-38^{O} of anteversion. [23] Snijders et al failed to find a consensus for ideal acetabular component orientation due to variations in methods for analysis in studies collected through systematic review. [24]

It is known that other elements also influence total hip component positioning such as pelvic inclination and obliquity. [25] Pelvic orientation depending on positioning can significantly vary when using the anterior pelvic plan on lateral radiographs on the pelvis. [26] A change in pelvic inclination of 1^{O} has been shown to change functional cup anteversion by roughly 0.7^{O}. [27]

2.5 Consequences of Total Hip Malposition

Accurate implant positioning is important in stability and prevention of impingement of the total hip replacement. Appropriate positioning of components may help to avoid pelvic osteolysis, acetabular component aseptic loosening, impingement and intercomponent polyethylene wear due to a vertical cup position. [28,29]

One of the major risks of revision surgery is dislocation post total hip replacement. Dislocation affects 1-4% of total hip replacement patients, with 77% occurring in the first year postoperatively. [30] In the Canadian Joint Registry, instability is the third most common cause of revision accounting for 14.8% of revision cases. [1] Similar to the Canadian registry, instability accounts for roughly 15% of the hip revision in the UK registry. [31] The financial consequence of early dislocation within the early postoperative period has been estimated to cost 342% of the primary cost. [29] The risk of dislocation is multifactorial, categorized by patient and surgical factors. Patient host factors include previous surgery, dementia, inability to follow postoperative rehabilitation, female sex, and neuromuscular disease. The surgical factors are focused on implant selection, implant position, restoration of offset and leg length, and surgical approach.

With high volume of cases, the risk of instability decreases. One study found that for every 10 cases, there was a 50% reduction in a surgeon's dislocation rate. [32] It has been found that increasing age is a risk factor for dislocation, with a bimodal distribution with high dislocation prevalence in <50 and >70-year-old patients. [33] Body mass index greater than 30 has been shown to be associated with a greater risk of dislocation in meta-analysis. [34] One study demonstrated that early dislocation was more frequently seen in patients with a BMI> 35, with a 5% increase for every unit BMI increase above 35. [35] Patients with a spinal fusion have been shown to have a higher rate of dislocation. A single level fusion was also associated with dislocation rate of 1.5%, while a two level and three level fusion were associated with a 2.92% and 4.12% respectively. [36] Inflammatory conditions like ankylosing spondylitis have also demonstrated higher risk of dislocation. [37] Patients with a diagnosis of avascular necrosis had twice the risk of revision for instability. [38]

Specifically, cup version has been implicated in directional implant instability. In one study, cup position with respect to Lewinnek's safe zone was found to be an independent risk factor for instability with an odds ratio of 1.88. [39] Lewinnek et al established the safe zone after reviewing a series of 300 total hip replacements which had a dislocation rate of 3%. The dislocation rate was 1.5% within the safe zone versus a 6.1% dislocation rate outside this zone. [40]

Coventry et al found that with a cup position of 7-10 degrees of retroversion was associated with 50% of posterior dislocation in their study. [41] McCollum and Gray proposed a safe zone of 20^{O}-40^{O} of anteversion particularly in the posterolateral approach. [42] A cup anteversion of greater than 25^{O} has been linked to increased anterior instability. [28] Acetabular components with greater than 20^{O} had a 6.3 fold increased risk for anterior instability. [43] A study by Biedermann et al demonstrated similar findings to Lewinnek et al in their series of 127 dislocations. The study found that an abduction target of 45^{O} and $15^{O\,-}$ of anteversion had the lowest incidence of instability. Components with <10^{O} of anteversion lead to a sixfold increased relative risk for posterior instability.[43] A CT scan study found that patients with posterior orientated instability were found to have cup position with less than 20^{O} in anteversion. [44] One study through computer simulation indicated that ideal cup abduction is in the range of 45^{O}-55^{O} , however with this position comes unacceptable higher wear rates. [45]

The malposition of acetabular components has been thought to influence wear rates and long-term survival of total hip replacements. Little et al examined 43 THAS with conventional polyethylene with 49-month average follow up. Abduction angle greater than 45 degrees had a mean wear rate of 0.18mm/year wear rate. [46] Patil et al found that a 40% increase in mean linear polyethylene wear was noted in cup placement greater than 45^{O} abduction angles.[47] Kennedy et al found that with increasing inclination with a mean angle of 61.9^{O}, this led to pelvic osteolysis in 24% of hips. Asymmetric polyethylene was observed in 5.1% of hips with high inclination. [48] Del Shutte et al examined wear rates of cemented all polyethylene acetabular components and the effect of abduction angle. Their study did not find a correlation between degree of abduction and polyethylene wear. [49] The high wear rates seen in older studies is likely attributed to the use of conventional polyethylene. Goyal et al found no significance between cup inclination and use of highly crosslinked polyethylene wear. [50]

Crowninsheild et al found that maximal tensile stress on polyethylene was five times greater when placed in a vertical cup position and use of 40mm heads or greater. [51] Waewasawangwong and Goodman found in case report that despite the use of highly cross-linked polyethelene, a vertical cup position, thin polyethylene thickness and large femoral head led to fracture of superior rim at the locking groove of the liner. [52] Tower et al also concluded that thin polyethylene liner, vertical cup alignment and decreased mechanical properties can lead to failure of the rim. Inclination angle of greater than 65^{O} with a thin polyethylene liner has been found to increase failure of highly crosslinked polyethylene bearing. [53]

The abduction angle greater than 55^{O} of the acetabular component has been found to lead to increasing levels of cobalt and chromium release in metal-on-metal bearings by De Haan et al. [54] In ceramic-on-ceramic bearings, Sexton et al found that high cup inclination, high femoral offset, lateralization of hip centre or extremes of acetabular anteversion were predictors of squeaking. [55] Griffin el al reported that acetabular component increased anteversion or cup inclination was an integral factor leading wear and metalosis in metal-on-metal bearing surfaces. [56]

Component position also plays a role in the degree range of motion for the patient. Kummer et al reviewed range of motion in sawbone models. The study found that cup anteversion greater than 20^{O} and abduction angle greater than 45^{O} led to limitations in hip flexion, internal and external rotation. [57] D'Lima et al found through computer modelling that acetabular cup abduction less than 45^{O} led to decreased flexion and abduction of the hip. In contrast, abduction greater than 45^{O} led to decreased adduction and rotation.[58] Malposition of the cup can lead to pain due to impingement post hip replacement. Trousdale et al found that retroverted cup positioning leads to psoas impingement via the anterior rim of the acetabular shell. [59]

2.6 Traditional Technique of Acetabular Component Positioning

Prior to the advent of computer navigation, surgeons relied on mechanical devices to physically track acetabular component positioning. The mechanical devices are reliant on bony landmarks, gravity assisted systems or use of pins to control component positioning. These conventional manual techniques have limitations in reproducibility given that patient position, specifically pelvic position can change during the procedure.

Conventional positioning of the acetabular component has been demarcated by the anterior pelvic plane (APP) orientation. Robinson et al initially described the concept of the APP in 1922. [60] It consists of the anterior superior iliac spines (ASIS) and the pubic symphysis. Using an intraoperative mechanical alignment rod, surgeons would assess the acetabular cup position based upon anatomical landmarks. However, with conventional techniques, there has been wide variability and inaccuracy in cup placement. A study conducted by Callanan et al, found that only 62% of 1952 hip replacements were within their desired inclination target, demonstrating the inaccuracy of referencing the anatomic landmarks of pelvic orientation and patient positioning. [61] Most computer assisted navigation systems rely on the APP as the reference plane in a 3-dimentionsional (3D) system to help determine component positioning. [62]

McCollum and Gray suggested using the sciatic notch as a bony landmark guide. [42] Maruyama et al recommended the use of the acetabular notch angle. [63] Sotereanos et al advocated using the lowest point of the acetabular sulcus found on the ischium, prominence of superior pelvic ramus and superior point on the acetabular rim to guide acetabular component placement. [64]

Another traditional landmark used for acetabular orientation is the transverse acetabular ligament (TAL). This is usually used in conjunction with mechanical alignment jigs to obtain implant positioning. A study conducted by Kelley and Swank examined the use of the TAL reference for cup position and found 82% and 71% of cups fell within Lewinnek's safe zone for inclination and anteversion respectively. [28] Despite studies demonstrating good results using the TAL as an adjunct, many times the ligament is not identifiable. [65] The variability in the TAL has been demonstrated to have a wide range of natural anteversion of 5.3^{O} to 36.1^{O} on MRI study. [66]

McCollum and Gray pointed out that in the lateral position, the lumbar spine's lordotic curve flattens and the pelvis could be excessively flexed to 35^{O}. The acetabulum may subsequently be abducted towards the distal end of the table by 10-15^{O}. This positioning then leads to inaccuracy of mechanical alignment outrigger devices, which rely on relation of the table and body position to reference cup positioning. [42]

Outlier placement of component positioning has been attributed to up 3% of primary hip dislocations. [67] The estimated error of cup positioning has been reported as high as 26-78% with the use of conventional freehand techniques. [40,68–70] It has been reported that traditional non-navigated placement of component position leads to variations of

12^0-21^0 degrees in the literature. The use of mechanical jigs and freehand technique have been reported to achieve an accuracy of 44 to 88% in some studies. [71]

A study by Digioia et al demonstrated the inaccuracy of mechanical outrigger alignment guides in the lateral position due to pelvic position. It was found that 78% of acetabular components were deemed to have unacceptable alignment. [72] Another study demonstrated using mechanical outrigger devices led to almost half of the acetabular components, twenty-one of fifty cases, being placed outside the target zone. [70] Saxler et al found that conventional freehand technique led to only twenty-seven of one hundred and five acetabular components being placed within the target safe zone. [69] A study by Goyal et al demonstrated only 43.6% of cases fell within the Lewinnek safe zone in the traditional lateral approach. [73]

The use of fluoroscopy in total hip replacement has been integrated by surgeons to assist in placement of components. With the direct anterior approach, the use of fluoroscopy with a supine positioned patient allows for seamless integration. A study by Rathod et al found decrease in variances with use of fluoroscopy in the direct anterior approach versus a comparative posterior approach group.[74] When compared to mechanical jigs, the use of fluoroscopy was 2.3 times more likely to be placed within Lewinnek's safe zone in one study by Beamer et al.[75] [75]The accuracy of intraoperative fluoroscopy is influenced by several factors, including a learning curve associated with interpretation of obtained intraoperative images, pelvic position, and patient position. One study conducted found that intraoperative fluoroscopy underestimated the cup inclination in comparison to post operative radiographs while anteversion was overestimated in comparison to follow up AP radiograph films.[76]

2.7 Hip Navigation

The innovation of computer navigation in hip replacement surgery began in 1992.[28] Navigation is defined as a tool that provides information regarding patient anatomy and surgical implant positioning in reference to this. [77] Dealing with rigid surgical instrumentation and bony landmarks make orthopaedic procedures ideal to implement navigation technology.[78] William Bargar was the first to integrate computed tomography-based navigation system in joint replacement, with the goal of accurate femoral component placement.[28] The philosophy of this technology is to provide the surgical team with intraoperative real-time data to allow for accurate execution of pre-operative planning.[29]

Approximately 97% of hip replacement surgeries in the United States are performed using conventional technique without navigation technology.[79] The use of hip navigation and robotics was only found in 1.9% of 130,000 hip replacements in a database study conducted by Boylan et al. Adoption of technology was primarily seen at centers offering private insurance healthcare and high-volume institutions predominantly. [80] The perceived barrier such as increasing surgical time linked with the learning curve of computer-assisted surgery (CAS) has contributed to the lack of widespread adoption.[81] Valsamis et al demonstrated no difference in operative time when utilizing imageless navigation versus conventional instrumentation in their study.[82] In a large database study, computer assisted surgery was associated with an increased number of reoperations and superficial wound infections, however lower rate of minor adverse events like blood transfusion.[79]

With increasing pressures on healthcare systems to curtail spending, the use of technology like navigation has been seen as a luxury adjunct for surgeons. Initial purchase price, maintenance cost and additional surgeon reimbursement have been cited as potential factors in deterring many healthcare networks from investing in such devices. [83] Estimates of certain large console navigation systems have been reported to cost around $250,000 to purchase the device with added costs of maintenance and disposable instrument costs per case. [84]

There exist two main types of navigation: image based and imageless based system. The image-based navigation system relies on either intraoperative fluoroscopic images or a pre-operative CT scan. An imageless based system requires demarcation of anatomical bony landmarks on the patient to determine the anterior pelvic plane (APP). The APP is defined as both anterior superior iliac spine and the pubic tubercle. Imageless navigation requires the use of mounted sensors on surgical equipment such as the acetabular component insertion handle to feedback to the computer system, allowing accurate real-time feedback. Imageless systems consist of a four-stage procedure: set up, registration, planning and execution.[85] Imageless navigation technology uses kinematic and anatomical data received during the registration process to deliver intraoperative data to the surgeon. This data can be further made accurate with other sources of data such as anatomical imaging and implant selection.[86]

There exists both optical and electromagnetic tracking technology in imageless navigation. Optical tracking is based upon infrared stereoscopy to allow tracing the position of reference points placed on bony landmarks and surgical instrumentation. This tracking system requires that all reference points be visible to the stereoscopic camera, therefore any visual impedance can interfere with tracking. The technology is based upon utilizing optical system in combination with device cameras to gather positional data. This positional data is referenced off an infrared light from dynamic reference frame (DRF) in combination with light-emitting diodes or infrared light reflecting markers. [87] The dynamic reference frame (DRF) are trackers fixed to bony landmarks and surgical instrumentation that allow the camera to detect and determine spatial relationships. The major advantages associated with this technology are the accuracy and is not affected by ferro-magnetic objects within the field of view of the stereoscopic camera. Electromagnetic tracking creates an electromagnetic field in surgical field, with determination of the position of bony landmarks and surgical instruments with trackers. This technology does not require visualization of a camera required in optical tracking. However, instruments with ferro-magnetic properties can disrupt the accuracy.[78] Imageless navigation also makes assumptions like pelvic positioning and overall patient positioning to provide intraoperative readings. It is therefore susceptible to changes in pelvic tilt and overall patient positioning.[26] The learning curve for imageless navigation is around 3 to 5 cases.[88] A significant advantage of imageless navigation is the avoidance of parallax and operator error with imaging. [89]

One of the major limitations of imageless navigation systems presently is the level of accuracy for registration of pelvic reference points. There have been concerns regarding soft tissue density overlying the reference points for the anterior pelvic plane. A study examining soft tissue density overlying these reference points found that anteversion was most affected with increasing soft tissue density. The study found that soft tissue overlying the pubis could be 5.7 +/- 3.4mm thicker than on the

ASIS, leading the mean underestimation of anteversion by as much as 2.8^{O} +/- 1.8^{O} .[90] The other major issue is that systems do not account for the level of pelvic tilt, which can play a major role in accuracy of overall component positioning. Pelvic tilt has been shown to influence definitive anteversion, with a 1^{O} change in ventral-to-dorsal tilt is associated with a 0.8^{O} change in acetabular anteversion. To address this, the use of invasive techniques like direct puncture of soft tissue to register bony landmarks has been adopted in some system workflows. With this invasive registration comes the risk of morbidity like infection, bleeding, fracture and mechanical pullout. [91]

Two major studies have demonstrated concerns in the reliability of APP. Barbier et al found significant discrepancies in mean anteversion between intraoperative and postoperative findings. The intraoperative mean anteversion was 20.9^{O} compared to 29.5^{O} post –operatively. The significant difference in mean anteversion was attributed to difficulty in establishing the APP with registration and inter-observer variation intra-operatively.[92]

A study comparison of imageless navigation versus traditional technique found that cup position was reproducible to within 5^{O} of desired anteversion and inclination as compared to cups placed with traditional jigs. [93] A prospective randomized control trial compared the accuracy of component positioning with the use of conventional technique versus imageless navigation in 130 patients. The study did not show any improvement in cup inclination accuracy however did demonstrate improved accuracy in anteversion with navigation.[94] In contrast, a retrospective review of navigated THAs by Suksathien et al demonstrated significance in mean anteversion and inclination accuracy. All navigated cups fell within the safe zone versus only 48.4% of conventional cups were within the safe zone.[95]

Fluoroscopic guided navigation systems are reliant on intraoperative images taken of the pelvis, which can be performed in the supine or lateral position. Although an x-ray technician and imaging equipment are required in the surgical workflow, the patient does not require repositioning during point registration like imageless based technology. The use of image guided navigation is reliant on utilizing landmarks like the anterior pelvic plane (APP) to determine component and hip position. The APP however is not always level, and therefore susceptible to incorrect patient positioning and deformity. Some systems attempt to overcome this by using the functional pelvic plane (FPP) which is defined in the supine position on the CT table. The pelvis is axially manipulated until both ASIS are within the same horizontal plane and the inter teardrop line is instead adopted as the mediolateral plane. [87]

Image dependent navigation has demonstrated overall reduction in components placement outliers when compared to manually placed components. [101] Suggested limitations of this technology include the need for c- arm fluoroscopy machine, radiolucent operating room table and projection errors associated with obesity and pelvic positioning.[28] The major concern in image-based systems, including CT navigation, is the radiation risk posed to patients and the additional time added to the surgical planning and workflow.[29] With intraoperative fluoroscopy use in the direct anterior approach, the maximum dose of radiation was achieved in the first 100 cases. Performing more than 189 DAA hip cases per year has been hypothesized to have long term health effects. [96,97]

Kalteis et al conducted a study examining conventional technique, computed tomography based navigation and imageless navigation accuracy in the direct lateral approach. The study found that conventional technique led to only fourteen of the thirty-acetabular components placed in Lewinnek's safe zone. Both CT and imageless navigation led to comparable results in terms of components placed within the safe zone.[98] Lass et al conducted randomized control trial comparing conventional freehand technique to imageless navigation in 130 patients in the direct lateral approach. The study found improvements in postoperative cup anteversion and reduction in outliers, however failed to find differences in patient outcomes or revision rates at two years follow up.[94]

Parratte et al conducted a long term follow up of 10 years of thirty hip replacements which utilised hip navigation and thirty hip replacements conducted with conventional technique. No difference was found between navigation versus conventional in terms of instability, function, wear, or survivorship.[99] A retrospective cohort study conducted by Bohl et al. found that the use of navigation was associated with a lower rate of dislocation (1.00% versus 1.70% for no navigation; adjusted hazard ratio

[HR]= 0.69; 95% confidence interval [CI]= 0.58 to 0.82; p<0.001) and aseptic revision of acetabular component (1.03% versus 1.55%; adjusted HR =0.75; 95% CI=0.64 to 0.88; p<0.001).[83]

Another large retrospective review of 475 total hip replacement patients utilizing the posterior approach was conducted. The study found 11 dislocations, all within six weeks post operatively, with a rate of 2.3%. Nearly all dislocations were associated with severe bony deformities, neuromuscular or cognitive disorders. The study concluded that navigation decreased the risk of instability in mild to moderate bony deformity patients and reducing outliers in terms of cup placement.[100] In assessing leg length, utilizing mechanical and navigated systems have all been susceptible to a degree of error, with reported discrepancies measuring 1 and 9 mm.[78]

A study by Domb et al compared, robotic-guided hip surgery, navigation guided, fluoroscopic guided and conventional techniques in posterior approach and direct anterior approach surgery in terms of accuracy of cup placement. The study found that robotics and navigation provided greater reliability in comparison to traditional techniques.[101]

A metanalysis of 13 randomised control trials, with 1071 hips, demonstrated that navigation led to a higher number of acetabular components being inserted in the safe zone parameters regarding anteversion and inclination. In terms of complications of instability post operatively, there was no difference between navigated and non-navigated hips.[102] A study by Moskal et al demonstrated decreased rate of instability in navigated THA patients in comparison to conventional technique.[103] A metanalysis conducted by Li et al, found that the use of navigation led to significant improvements in accuracy of cup anteversion and decreased in acetabular outliers. The study failed to find any differences however in abduction angle and average blood loss.[104]

A study by Inoue et al examined the concerns regarding prosthetic joint infection associated with integration of technology and subsequent increased operative time. Their study looked at CT navigation use and PJI and found no significant difference compared to non-navigated total hip replacement. The study found a 20-minute increase in operative time on average. [105] A retrospective study by Bohl et al found no association with navigation use and increase risk of periprosthetic joint infection based on Medicare database. [83]

2.8 Direct Anterior Hip Approach

Most national joint registries and surveys of hip surgeons around the world demonstrate that posterior approach followed by lateral approach is the predominant surgical approach to performing hip arthroplasty. Less than 5% of surgeons in the United Kingdom, Sweden and New Zealand utilise the anterior approach.[106] In Canada, a survey of surgeons reported that the direct lateral approach was the popular surgical approach at around 60% with posterolateral approach utilised by 36%.[107]

During a recent AAHKS (American Academy of Hip and Knee Surgeons) meeting, greater than 50% of attendees reported that the direct anterior approach (DAA) was their standard approach. The DAA has been steadily increasing, with a survey of surgeons reporting its use rising from 12% in 2010 to around 50% in 2019.[9]

The anterior approach was initially described in 1870 by Hueter and then by Smith-Petersen et al and the Judets. This approach is described as a muscle sparing approach. The patient is positioned supine. A skin incision is performed distal and lateral to the anterior superior iliac spine, careful to avoid injury to the lateral femoral cutaneous nerve. The initial intermuscular interval between tensor facia lata and satorius is used. Careful dissection is required to address the ascending branches of lateral femoral circumflex artery. The deep layer interval is between rectus and gluteus medius. As this is a muscular sparing approach, the abductor musculature is left unscathed.[106] With the use of the direct anterior approach, the gluteus medius is spared however up to 30% of direct anterior hips had damage to the tensor fascia lata. [108] After adequately exposing the capsule and femoral head, the neck cut is performed. The extraction of the femoral head allows the acetabulum to be addressed. Special instruments including double offset broach handles, offset acetabular preparation instruments, and femoral stems with anatomical design may be required in the DAA.[9]

The enthusiasm for this approach has been based upon the potential reduction of risk of dislocation, faster recovery, less pain and fewer surgical complications. The disadvantages associated with this approach are the steep learning curve, difficulty in utility in obese patients, difficulty in management of intraoperative or postoperative complications through the approach.

The other major concern with the DAA approach is the effect on the staff and surgeon during the procedure. The use of heavy lead aprons, increased risk of infection with use of intraoperative fluoroscopy, surgical team radiation exposure has all been cited as potential disadvantages of this approach.[109–111] In direct anterior approach, surgeons have been found to reach half of the recommended maximum dosage of radiation within the first 100 cases due to routine use of fluoroscopy. [96,97] A study by Curtin et al reported that after 157 fluoro-assisted direct anterior hips, the radiation exposure to the patient is equivalent to a mammogram around 3 mGy and roughly four times less than a chest CT (13mGy).[112]

A systematic review conducted found that most patient reported outcome scores demonstrated better mean scores at the first six weeks post operatively however no significant difference upon 6 month and 1 year follow-up in comparison to other surgical approaches. Operative time was lengthier initially due to the steep learning curve in direct anterior approach.[113] Parvizi et al found that the anterior approach was associated with less blood loss in comparison to the direct lateral approach.[114]

A systematic review found that the direct anterior approach had higher percentage of early discharge from hospital as well as cup placement in within the safe zone in comparison to posterior approach patients. [115] Anterior approach patients had a 26% shorter length of stay in comparison to posterior approach patients with a higher likelihood of discharge to home. [116] There was a 20% increase in operative time and higher lateral femoral cutaneous nerve injury in the direct anterior group. [117] When compared to direct lateral approach, the DAA was found to have less pain and shorter length of stay however blood loss and operative time was equivocal. [118] A study comparing direct anterior approach to anterolateral approach found no difference in blood loss, risk of transfusion, operative time or length of stay.[119] There was no significant difference in periprosthetic fracture. [116] In another study comparing direct anterior, posterolateral and direct superior hip approach; they found that there was no difference in readmission rates, dislocation, infection or deep vein thrombosis. [120] Infection rates were no different between DAA versus Non-DAA cohort in a recent systematic review and meta-analysis[121] [120]

The DAA has been reported to have a lower risk of instability as well.[9] The dislocation rate in direct anterior approach ranges from 0.17 – 1.2% in the literature. [122–124] Over 60% of patients with a single episode of dislocation will have recurrent instability, while 50% of patients will require revision surgery. [125]

One of the challenges of this approach is exposure and placement of components given limited visualization of the acetabulum. High body mass index, wide or horizontal iliac wing, and surgical approach make placement complex. The use of navigation and intraoperative fluoroscopy has been adopted to overcome these patients and surgical factors that make accurate component placement challenging.[126]

A paper by Free et al determined that pre-operative radiographic signs influenced component placement. Coxa profunda predicted cup anteversion falling outside acceptable range while an increased centre edge angle predicted postoperative leg length discrepancy. Decreased neck-shaft angle and lower preoperative leg length discrepancies (LLD) were found to be predictive for femoral stem coronal malalignment.[127] In one study by Lin et al, the BMI of 30-34 was associated with 7.4 higher odds of unacceptable inclination and restoration of offset in DAA hips. Rathod et al found that there was less variation in inclination and anteversion in DAA compared to posterior approach. Matta et al examined the DAA approach using fluoroscopy only and found that 96% of hips obtained target abduction angle (30-50 degrees) and 93% within acceptable anteversion (10-25 degrees). [128] The one major criticism of other papers analysing accuracy of component placement utilise the safe zone of Lewinnek, which was originally based upon posterior approach. It is likely that each approach including the direct anterior approach have slightly varied "safe" zones.[129] In a cadaveric study, Nogler et al found that imageless navigation improved accuracy of cup placement in the direct anterior approach.[130] Debi et al found that in direct anterior approach, they had fewer components as outliers outside the safe zone in comparison to anterolateral approach. The use of fluoroscopy was however utilised only in the direct anterior approach hips.[131]

2.9 Radiographic imaging of the hip

Plain radiograph imaging has been the standard diagnostic tool for surveillance of the hip joint. The common radiographic views consist of the anteroposterior (AP) pelvis view and cross-table lateral view of the hip. This imaging modality has been utilised in the post-operative evaluation of component position and alignment. In long term follow up, plain radiographs can help detect wear, osteolysis and implant failure. The two main angles described in acetabular component positioning are anteversion and inclination.

Inclination is defined as the angle between the transverse axis and face of the acetabular shell in the coronal plane. This angle is measured off a horizontal line across bony landmarks such as the tear drops or ischial tuberosities.

Anteversion is defined as the angle between the longitudinal axis and opening face of the acetabular shell in the sagittal plane. CT imaging remains the most accurate for measuring acetabular component anteversion, however due to impracticalities like cost and risk of radiation, x-ray imaging is more appropriate modality. There is no consensus on measurement of anteversion. Historically, protractors were used to measure anteversion. Mathematical formulas and computer program with edge detection software have been devised to calculate anteversion and inclination.

Woo and Morey's method and ischiolateral method are techniques, which measure anteversion from a cross-table lateral. Woo and Morey's method uses a line perpendicular to the horizontal plane of the radiograph and the opening face of the acetabular component. The ischiolateral method uses a reference line perpendicular to long axis of ischium. The angle between the reference line and acetabular shell on cross table lateral determines the radiographic anteversion of acetabular component.[67]

There are several methods used to determine anteversion on an anteroposterior radiograph. One of the methods to assess anteversion on a single anteroposterior radiograph is the Lewinnek et al method. This is based upon the calculation of the version = arcsin (D1/D2). The D1 is denoted as the short axis of the cup, while D2 is the long axis of the acetabular ellipse. [40] The Liaw et al technique relies on the calculation of version = $\sin^{-1} \tan \beta$. [132] Pradan's technique is again based upon the AP radiograph of the pelvis, utilising a formula of version = arcsin (p/0.4D). [133] The D denotes the long axis of the ellipse. Lee et al found comparable accuracy of Lewinnek's method to Pradhan et al, and Liaw et al techniques for anteversion assessment. [134]

Limitations in use of the cross table lateral radiograph is that there is a degree of overestimation of anteversion and may not be a reliable method. [135] The anteversion measured on the lateral is affected by pelvic tilt in the sagittal plane. [24] As dislocations have been found to occur in all zones, there is an implication that the "optimal" position is patient specific. [24] CT has been found to be superior to plain radiographs in determination of anteversion. [136–138]

One of the other major determinants of hip stability in addition to acetabular component, is the femoral implant position. The femoral component version is difficult to assess on single plain radiographs, often requiring CT imaging or biplanar radiographs. CT imaging is not conducted during weight bearing, has high cost and radiation risk associated for routine use of interrogating acetabular component positioning. Esposito et al found that the use of biplanar radiographs provided a reliable safe modality of interrogating combined anteversion. [139] The concept of combined version is difficult to assess on plain radiographs.

2.10 Summary

Total hip replacement is the definitive treatment for end-stage joint disease of the hip. With increasing numbers of hip replacement surgery being performed, it is important to determine whether navigation technologies demonstrate improvement in terms of acetabular component placement when compared with traditional techniques.

Navigation accuracy and use has been explored in the comparison with mechanical instrumentation and their use in other surgical approaches like the modified Hardinge and posterolateral approach to the hip. As the use of the direct anterior approach becomes more popular amongst hip surgeons, a comparison of intraoperative fluoroscopy, imageless navigation and image guided navigation with regards to accuracy of acetabular positioning is important to investigate.

Chapter 3

3 Objectives

3.1 Research Objectives

Our primary objective was to compare the accuracy of component positioning in direct anterior approach hip replacements using conventional fluoroscopic technique, fluoroscopic image dependent navigation, and imageless navigation. The secondary objective of this study was to compare each technique with operative time and complications such as periprosthetic infection, periprosthetic fracture, and dislocation.

We hypothesized that the use of navigation would demonstrate improved accuracy in comparison to conventional technique. When comparing VELYS™ (image-guided navigation) and INTELLIJOINT HIP ® (imageless navigation) accuracy, we predicted that the use of the two navigation systems will be equivalent. We hypothesized that operative time would be increased with the use of navigation however complications would be similar across all groups.

Chapter 4

4.1 Study Design

Ethics approval was obtained from our institutional review board. Our institutional arthroplasty database was used to obtain patient information between 2016 and 2022 including their age, height, weight, gender, date of their total hip arthroplasty, laterality of the hip, duration of procedure, implant information and surgical approach utilised for the procedure. All total hip replacements were performed by two fellowship trained high-volume surgeons, each trained in the direct anterior approach and performing more than 250 direct anterior total hip replacements per year. Patients were collected in three groups.

4.2 Eligibility Criteria

The inclusion criteria included patients over the age of 18 who underwent primary elective total hip arthroplasty using the direct anterior approach, with diagnosis of end stage osteoarthritis or inflammatory arthritis. Patients with a diagnosis of hip dysplasia, post traumatic deformities, declined consent for use of clinical data for research, patients who underwent alternative hip approaches, and revision surgery were excluded.

4.3 Sample Size

We hypothesized that the rate of malposition of components would be decreased from 40% to below 15% using either navigation system. Using standard assumptions of a=0.05 two-sided, power = 0.80, chi-squared test, at least 49 patients would be required in each group. This power calculation was based upon a previous study conducted by Kalteis et al which estimated a decrease of 50% to below 15% using navigation.[98]

Acetabular components used in the study were all press fit, hemispherical shells, and included), R3™(Smith and Nephew, Memphis, TN), Pinnacle®(Depuy, Warsaw, IN) and Trident®(Stryker®, Kalamazoo, MI).

4.4 Intervention

The anterior approach was initially described in 1870 by Hueter requires the patient to be positioned supine. One of our surgeons used a normal operating table while the other surgeon preferred the HANA® table (Mizuho, CA) during direct anterior hip replacement procedure in the study. A skin incision is performed distal and lateral to the anterior superior iliac spine while being careful to avoid injury to the lateral femoral cutaneous nerve. The initial inter-muscular interval lies between the tensor facia lata and sartorius. The deep layer interval is between rectus and gluteus medius. After adequately exposing the capsule and femoral head, the neck cut is performed. The extraction of the femoral head allows the acetabulum to be addressed.[9]

During the direct anterior hip replacement procedure, conventional intraoperative fluoroscopy, image guided navigation (VELYS™) or imageless navigation system (INTELLIJOINT HIP ®) was utilised. In the conventional technique group, the surgeon utilised intraoperative fluoroscopy to aid in cup placement. This would require a C-arm fluoroscopy machine and radiology technician to obtain intraoperative imaging of the hip. The patient would be in the supine position during the procedure and obtaining imaging.

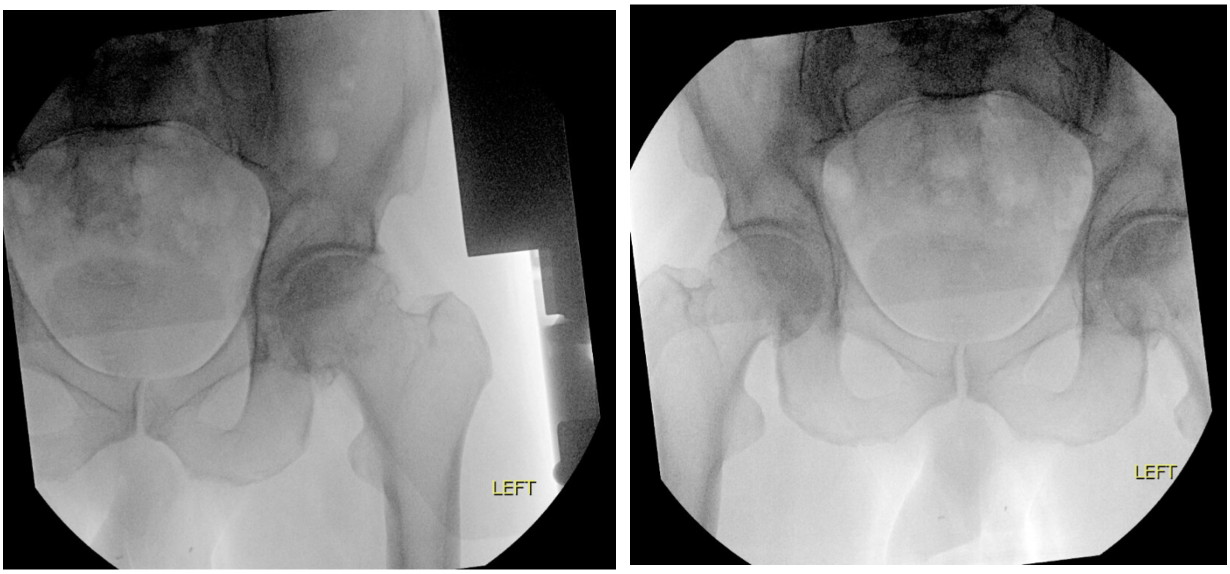

Figure 5 – Anteroposterior Pelvis radiograph and Anteroposterior Hip radiographs Reference imaging required for the VELYS™ Navigation system.

VELYS™ system is a fluoroscopy dependent navigation which requires initial baseline AP pelvis radiograph and AP of the operative hip for landmarking (Figure 5). These images are transferred to the VELYS™ separate display, and the surgeon or his assistant must identify anatomical landmarks such as the anterior superior iliac spine (ASIS), tear drop and pubic tubercle. The software then enables the measurement of acetabular position on this display on subsequent images. This system requires no devices within the surgical sterile field. The software imaging is shown in Figure 6.

Figure 6: VELYS Navigation screen
First image of the reference AP pelvis is utilised for establishing bony landmarks as references for cup position. Second image demonstrates software determination and readout of cup inclination and anteversion.

INTELLIJOINT® system is an imageless navigation program which requires an infrared optical camera and tracker which are placed within the surgical field. This is demonstrated in Figure 7. Imageless based navigation systems utilise the anterior pelvic plane (APP) to determine component position spatially. Solid pins are placed by the surgeon into the iliac wing to establish a stable platform for the optical camera within the surgical field. The navigation system requires registration of anatomical bony landmarks on the patient to determine the APP which is the bilateral ASIS and pubic symphysis.

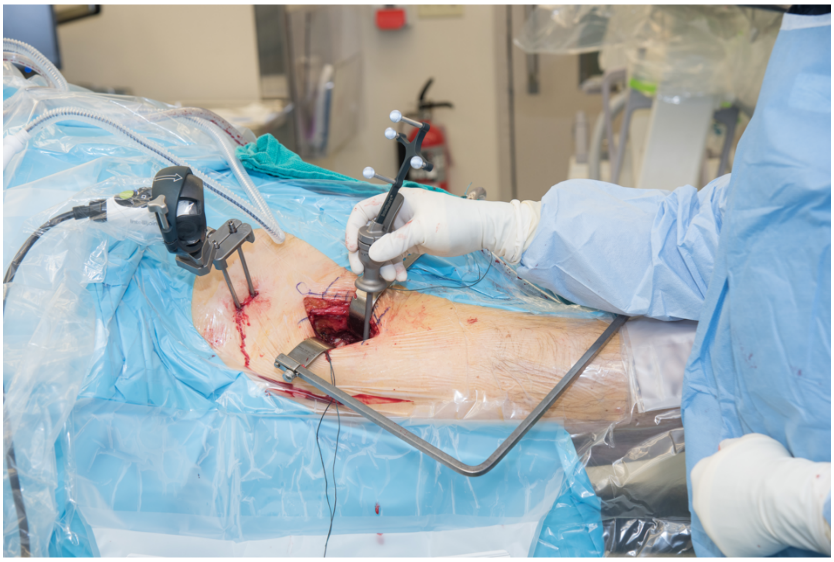

Figure 7: INTELLIJOINT® optical camera and probe
Registration of bony landmarks is being performed in the image.

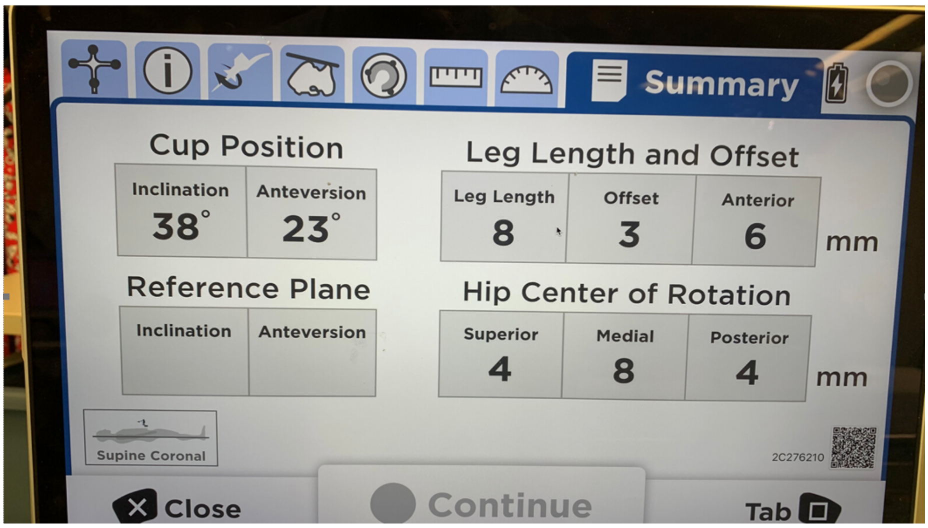

Figure 8: INTELLIJOINT® software screen
The image is depicting the software readout of the intraoperative cup inclination and anteversion.

Both navigation systems provided the surgeon with intraoperative cup anteversion and inclination values. This is demonstrated in Figure 6 and Figure 8. Intraoperative radiographs of cup position were obtained for analysis of anteversion and inclination in the fluoroscopy only cohort. Post-operative AP radiographs were analysed in all three cohorts to determine final inclination and anteversion.

4.5 Data Analysis

The conventional fluoroscopy and image guided navigation group was collected retrospectively while the imageless navigation group was collected prospectively. The first five cases for each navigational group were excluded for learning curve of adoption of new technology. Radiographs were performed intraoperative and postoperatively at the 6-week follow up period. Anterior posterior (AP) pelvis was conducted according to our radiology department protocols. The patient was positioned in the supine position with legs internally rotated approximately 15^{O} with the beam directly centred on the pubic symphysis with a focus distance of 115cm. The AP radiograph of the pelvis suitability was evaluated by examining the symmetry of the obturator foramen, the central sacral line parallel to the pubic symphysis, an approximate distance of 3cm between the sacrococcygeal junction and pubic symphysis and ensuring that the ilioischial line was in line with the acetabular tear drop.

Using Picture Archiving and Communications System (PACS), we measured the radiographic inclination angle and anteversion both intraoperatively and postoperatively. Radiographs were analysed by two observers. A subset of the population was measured by both, to calculate the concordance correlation coefficient to confirm adequate inter-observer reliability. Differences in measurements, when present, were reconciled through mutual agreement. We utilised radiological definitions based upon Murray.[17] Inclination is the angle between longitudinal axis of body and acetabular axis while anteversion is defined by the angle between the acetabular axis and the coronal plane.[17] Inclination angle was measured between the face of the acetabular component and the horizontal axis drawn by connecting the intra-tear drop line. This is depicted in Figure 9.

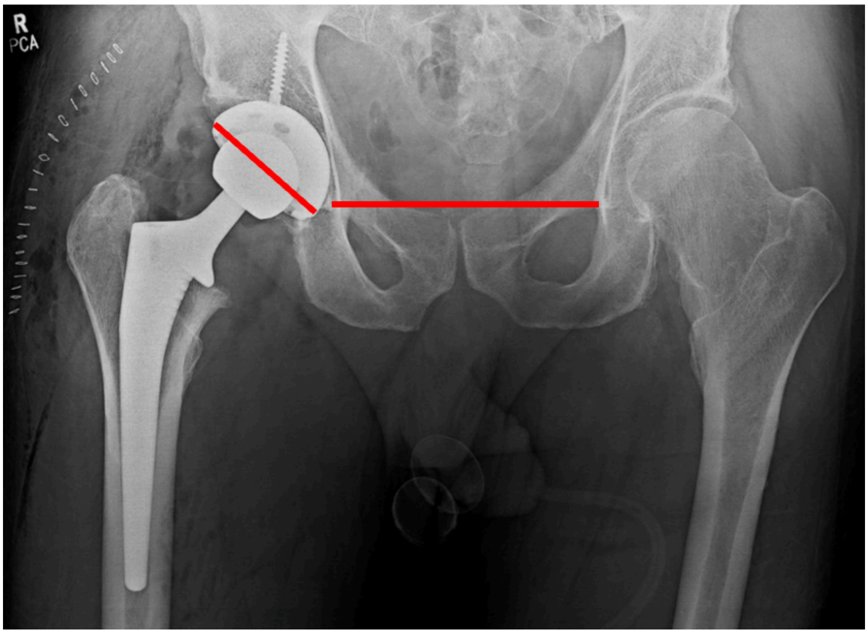

Figure 9: Inclination angle:
Inclination angle was measured between the face of the acetabular component and the horizontal axis drawn by connecting the intra-tear drop line.

Anteversion was measured using the technique described by Lewinnek et al. on a plain AP pelvis radiograph. This technique is depicted in Figure 10. This method of measuring anteversion on a plain radiograph has been shown to have high reliability and reproducibility. [134,140,141]

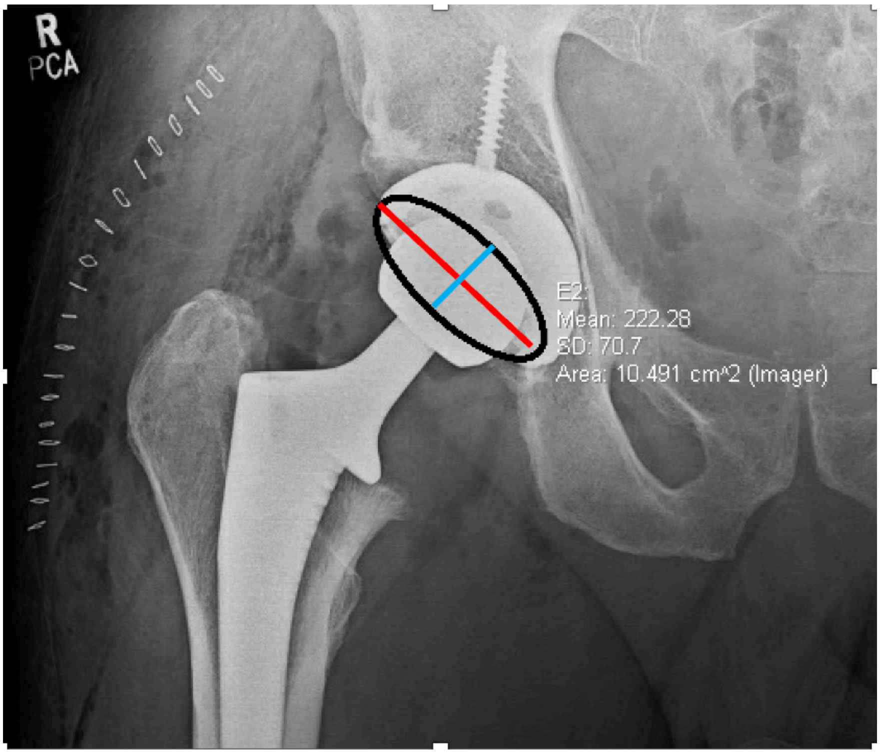

Figure 10: Anteversion Angle
Anteversion was measured using the technique described by Lewinnek et al. on a plain AP pelvis radiograph. This is based upon the calculation of the version = arcsin (D1/D2). The D1 is denoted as the short axis of the cup, while D2 is the long axis of the acetabular ellipse. Blue line is denoted as D1. Red line is denoted as D2.

The two surgeons in this study had different acetabular component targets. Surgeon A's target cup inclination and anteversion were 40 +/- 5 degrees and 20 +/- 5 degrees. Surgeon B's target cup inclination and anteversion were 35+/- 5 degrees and 15 +/- 5 degrees respectively. The accuracy of each method of cup positioning was evaluated by three methods. The primary outcome was to determine the percentage of cups which were placed within each surgeon specific safe zone. The second outcome was to analyse the absolute deviation of cup position determined by 6-week post-operative radiographs from target position, the mid-point of each surgeon's specific safe zone. This variation was defined as placement error. The intraoperative anteversion and abduction was compared to the post-operative cup position with review of post-operative radiographs. The deviation was defined as the estimated error.

The mean inclination and anteversion was reported for each surgeon's target for the three surgical groups. Anteversion and inclination were analysed as the absolute deviation from the target that each surgeon set for themselves. For example, a measured inclination of 47^0 for surgeon A, would be computed as a deviation of 7^0, since his target is 40^0. The same deviation, 7^0, would be reported if surgeon A had a measured inclination of 33^0.

Secondary outcomes included operative time and 60-day complications (dislocation, infections, periprosthetic fracture).

To assess the inter-rater reliability of the observation, the intraclass correlation coefficient (ICC) was computed for both, the anteversion and the inclination measures. The function *icc* of the *irr* package was used in R. Based on Mast et al. (2011) an ICC value > 0.75 was considered as acceptable.

Statistical analysis was performed using the chi-squared test for categorical data (sex) and analysis of variance (ANOVA) for continuous measurements (all others). For research questions with interaction terms, the interaction was first tested. If non-statistically significant, then the response variable (e.g. OR time) was individually tested for each explanatory variable (e.g. navigation system & surgeon). Only where statistical significance was found were Tukey Honest Significant Differences performed, using the function *TukeyHSD*. Adjusted p-values were used while performing multiple comparisons. Assumptions of homogeneity, independence and normality were confirmed.

To assess the accuracy of the intraoperative measure *versus* the postoperative measure of anteversion and inclination for all navigation system, a paired t-test was performed. A test was performed on each measure (inclination and anteversion) for each navigation system.

Statistical analysis was performed in R version 3.6.0 (R Core Team, 2017). Values of $p < 0.05$ were considered statistically significant.

Chapter 5: Results

The demographics across the three groups were similar as depicted in the Table 1. Age on average in the INTELLIJOINT® cohort was increased in comparison with the other two categories. There was a significant difference in operative time between the use of imageless navigation (INTELLIJOINT®) in comparison to conventional and image based navigation (VELYS™), with a mean operative duration of 75.5 mins compared to 65.8 and 68.9mins respectively. Table 2 demonstrates results for mean operative time. The inter-rater reliability demonstrated good agreement for radiographic analysis between observers for inclination (ICC = 0.855 (n=200) and anteversion (ICC = 0.894 (n=200).

Table 1 – Demographic description of the three navigational system patient groups. Letter indicate the groups, when significance is detected

	Conventional (n=50)	VELYS (n=50)	INTELLIJONT (n=50)	p-value
Age (yrs)	a	a	b	
Mean (SD; range)	63.3 (10.3; 44-87)	61.7 (12; 34-87)	68.9 (11.1; 42-88)	0.0045
Sex				
Women:men	27:23	27:23	25:25	0.899
BMI (kg/m^2)				
Mean (SD; range)	26.7 (5.1; 22.6-40.5)	27.9 (5.2; 19.3-42.5)	28.2 (4.6; 19.9-41.2)	0.274

Table 2 – Duration of total hip arthroplasty (THA) for the three navigational system.

	Conventional (n=50)	VELYS (n=50)	INTELLIJONT (n=50)	p-value
Duration of THA (mins)	a	a	b	
Mean (SD; range)	65.8 (8.54; 48-87)	68.9 (10.7; 43-101)	75.5 (10.8; 49-100)	< 0.0001

Our study analysed the absolute deviation of cup position determined by 6-week post-operative radiographs from target position, the mid-point of each surgeon's specific safe zone. This variation was defined as placement error. There was no significant difference regarding final cup position from desired targets of anteversion (P=0.08) and inclination (P=0.94) when comparing all three groups. The results are available in Table 3.

When assessing the estimated error, the accuracy of intraoperative and post-operative inclination and anteversion, the use of conventional fluoroscopy demonstrated significance in terms of inaccuracy for both parameters. The image guided navigation system demonstrated statistically significant inaccuracy in terms of anteversion between the intraoperative and postoperative cup position. The imageless navigation demonstrated low estimated error in both radiographic cup inclination and anteversion. The results are available in Table 4.

Table 3 - Deviation from the desired inclination (35-40°) and anteversion (15-20°) by the three navigational system.

	Conventional (n=50)	VELYS (n=50)	INTELLIJONT (n=50)	p-value
Deviation from inclination target – Intraoperative				
Mean (SD; range)	5.6 (2.9; 0.1 – 12.2)	3.7 (2.9; 0 – 12)	5.6 (6.3; 0 -32)	*
Deviation from anteversion target – Intraoperative				
Mean (SD; range)	3.6 (2.9; 0 – 10.6)	3.9 (2.8; 0 – 15)	5.1 (5.2; 0 – 28)	0.115
Deviation from inclination target – Postoperative				
Mean (SD; range)	3.1 (2.2; 0.4 – 10.8)	3.2 (3.1; 0 – 13.8)	3.3 (2.7; 0.1 – 12.9)	0.94
Deviation from anteversion target – Postoperative				
Mean (SD; range)	4 (3.5; 0 – 15.55)	2.7 (2.1; 0 – 9.7)	3.6 (3.1; 0 – 11.8)	0.08

Table 4 – Accuracy of the intraoperative measures in comparison to the postop measures for the different navigation system.

	Conventional (n=50)	VELYS (n=50)	INTELLIJONT (n=50)
Accuracy of anteversion (p-value)	<0.0001	0.00043	0.409
Intraop Mean (SD; range)	15.4 (5.3; 4.4 – 25.1)	19.2 (5.5; 7 – 30)	16.2 (7.3; 3 – 43)
Postop Mean (SD; range)	18.8 (5.3; 7 – 32)	16.3 (3.5; 5.3 – 24.9)	15.5 (4.8; 3.2 – 25.6)
Accuracy of inclination (p-value)	<0.0001	0.774	0.698
Intraop Mean (SD; range)	32.6 (4.3; 23.8 – 42.8)	35.8 (6.3; 23 – 46)	36.7 (8.6; 15 – 6 7)
Postop Mean (SD; range)	37.2 (5.6; 28.4 – 47)	35.6 (5.6; 21.2 – 42.5)	37.1 (4.9; 27.1 – 52.9)

In terms of final cup positioning, Surgeon A achieved 59% (16/27 cups) within the specific target while Surgeon B obtained 48% (11/23 cups) when using conventional fluoroscopy only. The conventional group is depicted in Figure 11. With the use of image guided navigation, VELYS™, Surgeon A achieved 83% (20/24 cups) while Surgeon B obtained 69% (18/26 cups) within their defined zones. The VELYS™ group is depicted in Figure 12. With the use of imageless navigation, Surgeon A had 76% (20/26 cups) while Surgeon B had 50% (12/24 cups) within target zone. The INTELLIJOINT® group is depicted in Figure 13.

In terms of final component inclination, there was very similar standard deviations found between conventional and computer assisted navigation demonstrated in Figure 14 box and whisker plot. Final cup anteversion demonstrated smaller variation with a lower standard deviation seen with use of VELYS™ navigation in comparison to INTELLIJOINT® navigation or conventional technique seen in figure 15.

When comparing post operative complications, there were no differences across the three groups. There were no dislocations across the three groups. Results are available on Table 5.

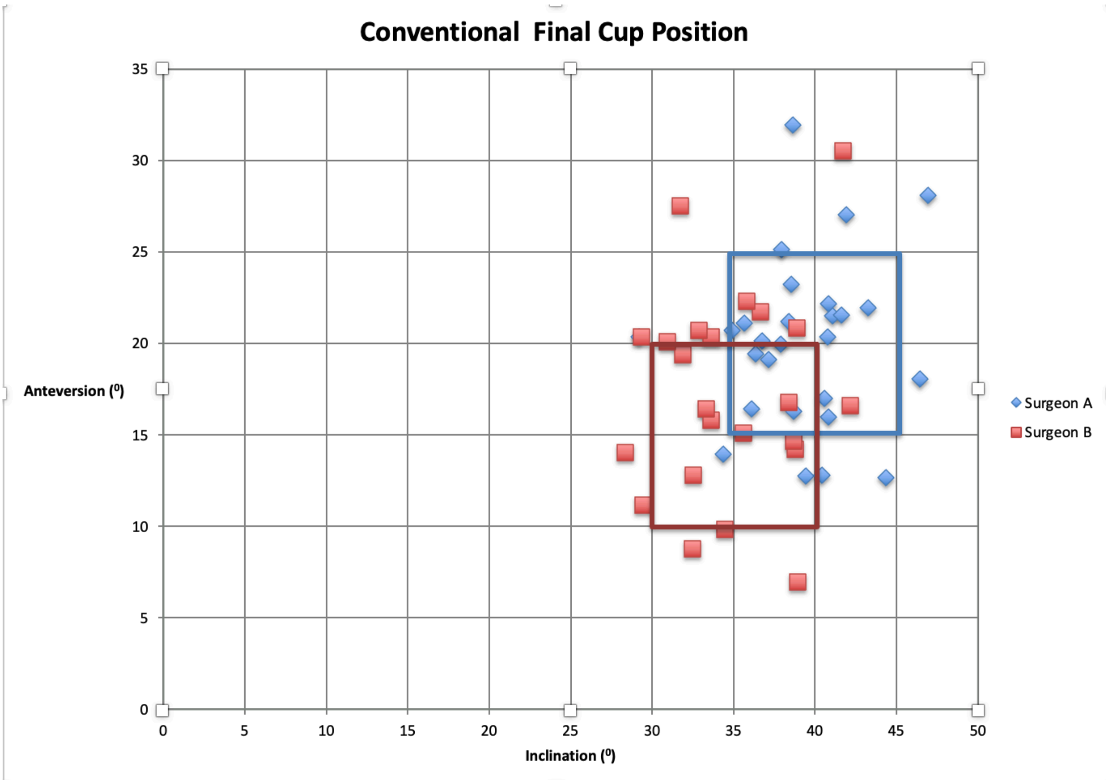

Figure 11: Conventional Fluoroscopy Final Cup position
Target zone is delineated by the colour coded box. Surgeon A defined in Blue with a target of inclination 40^0+/-5 and anteversion of 20^0+/-5. Surgeon B defined in Red with a target of inclination 35^0+/-5 and anteversion of 15^0+/-5.

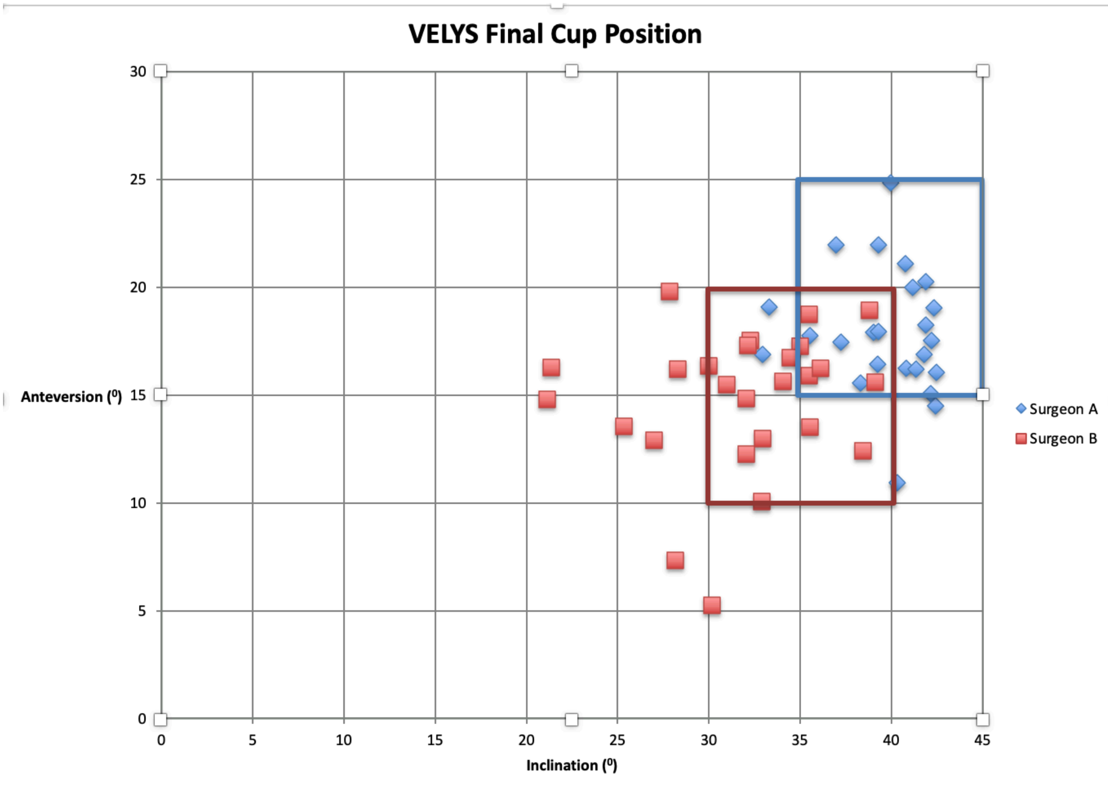

Figure 12: Image guided Navigation (VELYS^{TM}) Final Cup position
Target zone is delineated by the colour coded box. Surgeon A defined in Blue with a target of inclination 40^0+/-5 and anteversion of 20^0+/-5. Surgeon B defined in Red with a target of inclination 35^0+/-5 and anteversion of 15^0+/-5.

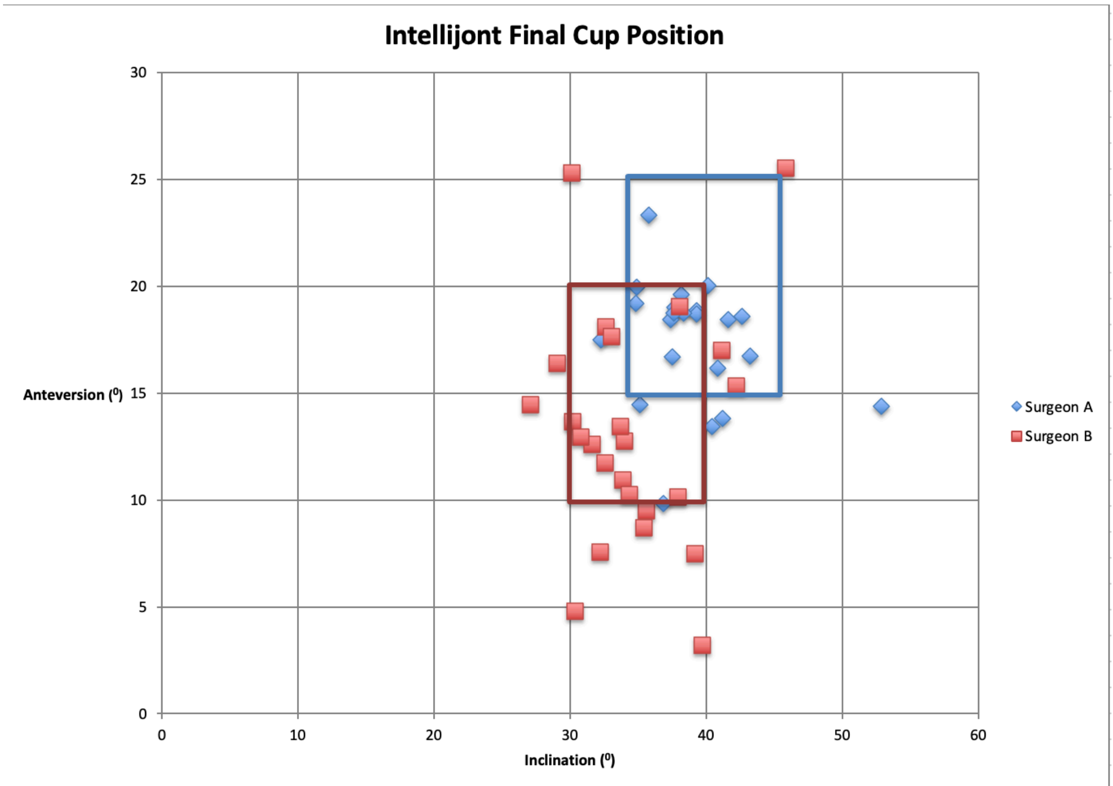

Figure 13: Imageless Navigation (INTELLIJOINT®**) Final Cup position**
Target zone is delineated by the colour coded box. Surgeon A defined in Blue with a target of inclination 40^0+/-5 and anteversion of 20^0+/-5. Surgeon B defined in Red with a target of inclination 35^0+/-5 and anteversion of 15^0+/-5.

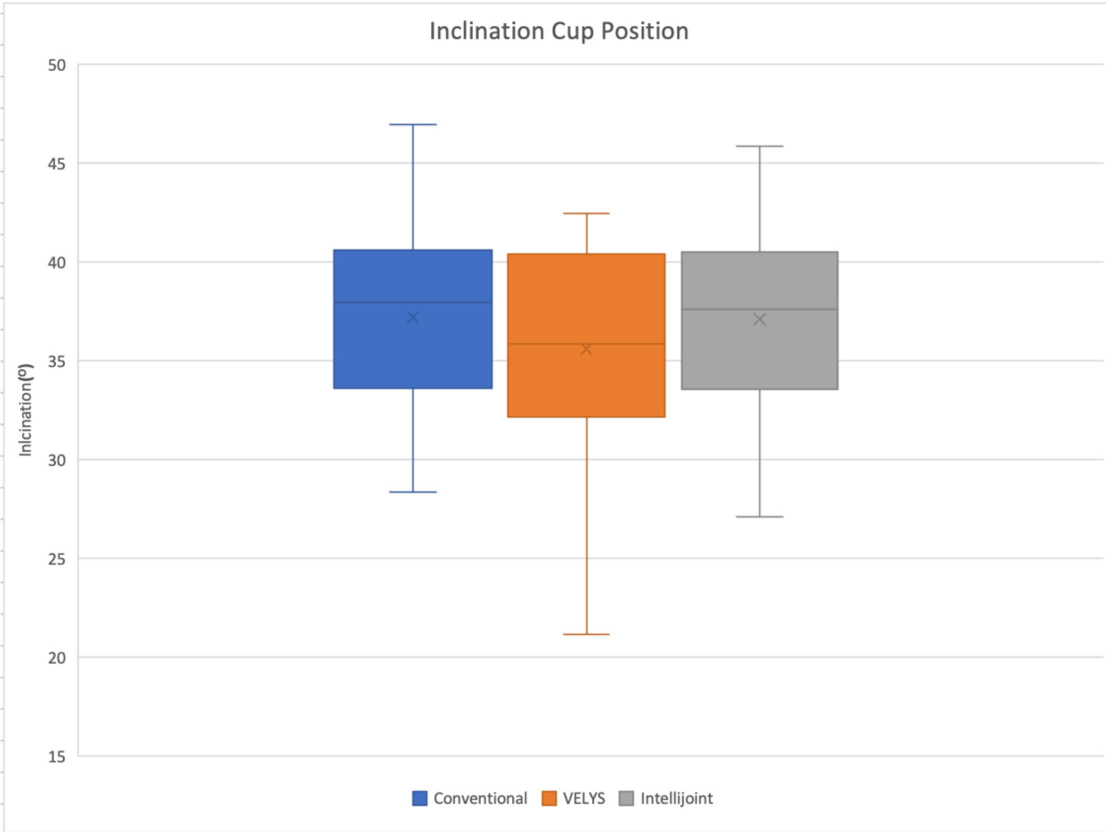

Figure 14: Final Inclination Cup Position
The boundaries of the boxes are indicated by the 25th and 75th percentile, with the mean value marked as the line within the box. Whiskers above and below the box indicate the 90th and 10th percentile.

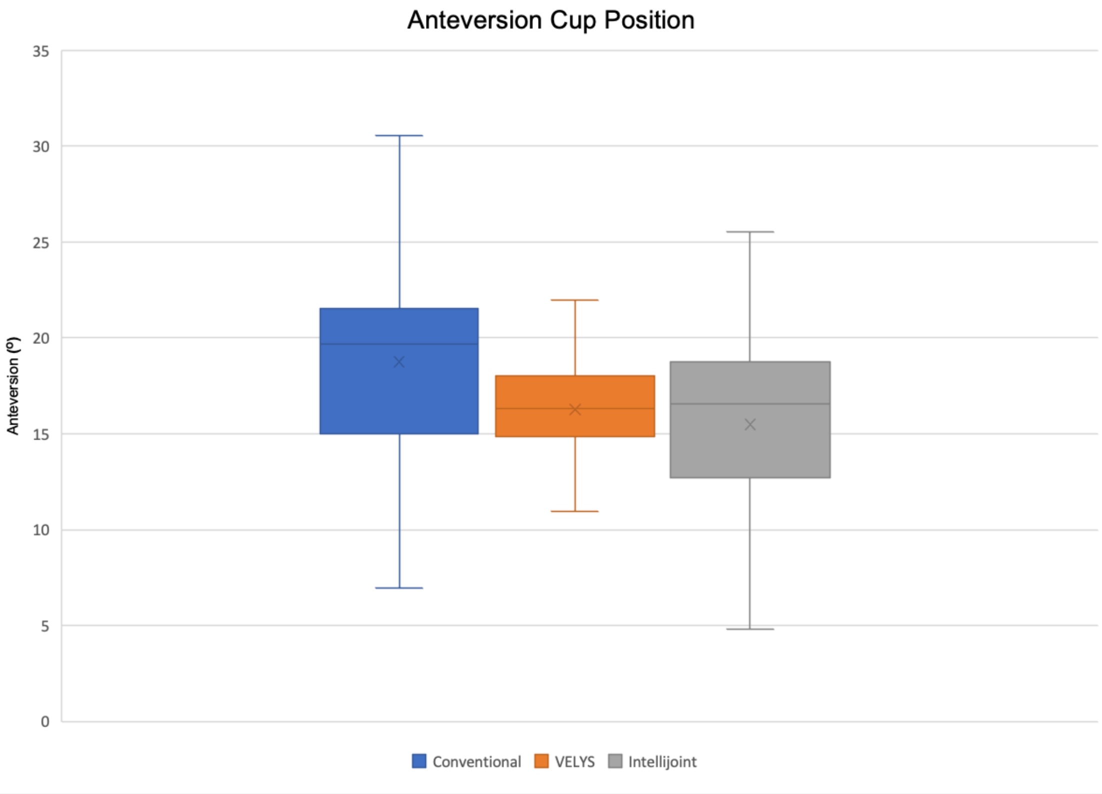

Figure 15: Final Anteversion Cup Position
The boundaries of the boxes are indicated by the 25th and 75th percentile, with the mean value marked as the line within the box. Whiskers above and below the box indicate the 90th and 10th percentile.

<u>Table 5: 60 Day Complications across all three groups</u>

Complications			
	Conventional	VELYS™	INTELLIJOINT®
Periprosthetic Infection	1	1	0
Periprosthetic Fracture	0	0	0
Dislocation	0	0	0

Chapter 6: Discussion

The accurate placement of total hip components is a three-dimensional consideration. We hypothesized that the use of navigation technology would demonstrate increased accuracy in comparison to conventional fluoroscopy. In our study, we demonstrated an improvement in reduction of outliers of component positioning with the use of image guided navigation and imageless navigation in comparison to conventional fluoroscopy. Our study utilised narrow target zones specific to each surgeon's preference for their ideal cup position. Surgeon A's target zone was defined as inclination 40+/-5 and anteversion 20 +/-5. Surgeon B had a target zone of inclination 35+/-5 and anteversion 15+/-5. Most studies published have adopted the much wider Lewinnek's safe zone as a study target zone. Lewinnek's safe zone is defined as of 40^{O} +/- 10^{0} inclination and 15^{0} +/- 10^{0} of anteversion.[19] This may have accounted for the difference in accuracy seen in comparable studies. For example, a study done by Chang et al, found that using imageless navigation led to no outliers from their target safe zone compared to ten conventional cases falling outside the zone. The study used a "safe zone" parameter of cup inclination 40^{0}+/- 10^{0} and anteversion 20^{0}+/-10^{O}.[86]

The estimated error, defined as the difference between intraoperative cup position from final cup position, was significant in the conventional fluoroscopy group for both inclination and anteversion. Image guided navigation (VELYS™) demonstrated significant estimated error with cup anteversion. Our study found that INTELLIJOINT® demonstrated a much lower estimated error of cup anteversion than the use of VELYS™ navigation and conventional fluoroscopy. This could be due to the challenges in obtaining fluoroscopic images, reproducing these images, identifying anatomic landmarks on the anteroposterior pelvis and hip radiographs, and patient positioning.

Our study found limitations of fluoroscopy use and image guided navigation in estimation of cup anteversion. Several studies have also reported that image-based navigation resulted in errors in anteversion evaluation. A study by Jennings et al found that the use of fluoroscopy in the direct anterior approach was only statistically significant for cup inclination, not anteversion. The study did find that use of intraoperative imaging led to high number of cups placed within the ideal safe zone.[142] Tannast et al evaluated fluoroscopy-based navigation. The study found no improvement in anteversion in comparison to conventional techniques citing that registration of the mid-point pubis led to inaccuracy.[143] Stiehl et al found similar variability in cup version accuracy when utilizing fluoroscopic guided navigation.[144]

The limitations seen with fluoroscopy use and VELYS™ image guided navigation may be linked to the limitations associated with obtaining accurate imaging. In direct anterior approach, positioning of the C-arm is crucial to accurate imaging and cup position interpretation. It has been reported that upwards of 100 cases are required to achieve refinement of appropriate C-arm positioning in DAA. [145] A 10-degree deviation in C-arm tilt angle may lead to 9 degrees error of perceived anteversion. [146] Conventional fluoroscopy is susceptible to pelvic tilt and extension leading to inaccuracies of estimating anteversion and inclination. [146,147] Shah et al report that the initial pelvic position tends to move into a position of extension by the time of cup impaction. The pelvis will roll as much as 9 degrees and 1 degree of pelvic roll prior to cup impaction in the direct anterior approach. This leads to 0.64^0 and -0.20^0 changes in anteversion and inclination. [147]

INTELLIJOINT® imageless navigation system demonstrated low estimation error rates in both cup inclination and anteversion in our study. With the imageless navigation system, the software makes assumptions upon the position of the patient being in a neutral supine position, parallel to the floor, to determine the anteversion and abduction angles. In a comparison of supine versus lateral positioning and the use of imageless navigation, the study conducted by Tetsunaga et al found no significant difference in reference to acetabular inclination and anteversion. This has been attributed to the fact that the anterior pelvic plane (APP) is the same bony landmarks utilised regardless of patient position. [148] Despite this, it has been reported that the use of the anterior pelvic plane (APP) has susceptibility to pelvic tilt and patient position variation. Pelvic tilt can range from 30 to 60 degrees, with a change in upwards of 10 degrees from a seated to standing position.[149,150] The issues with using APP are also rooted in the fact that patients have natural variations in pelvic tilt. Wan et al found that 8.6% had no anteroposterior pelvic tilt, 40.4% had posterior pelvic tilt of 1° to 9°, 12.6% had posterior pelvic tilt of 10° to 25°, 33.6% had anterior pelvic tilt of 1° to 9°, and 4.8% had anterior pelvic tilt of 10° to 20°. [151] Functional pelvic orientation has been proposed as an alternative, based upon spinopelvic axis. [87]

Variation in pelvic tilt can significantly alter the navigations system's interpretation of the cup position leading to increased margin of error in presented data. Gofton et al found that placing the patient in the supine position during acetabular component placement demonstrated less variability in acetabular orientation. The lateral position commonly used in the posterolateral and Hardinge approach demonstrated a higher proportion of deviation $>10^{O}$ in anteversion and/or inclination in comparison to the direct anterior approach. The lateral position has been attributed to greater variation in pelvic position due to the difficulty of securing and maintain pelvic position throughout the entire surgical case. The study found that a difference of greater than 10 degrees can lead to a 3.5-fold increase in risk of malposition. [71] . In our study, patients were positioned in the supine position for their hip replacement. A standard operating table and HANA® table were utilised by the two surgeons included in the study. The HANA® table has a groin post allowing for counter traction and provides a fixed point for stabilisation of the pelvis. The standard operating room table does not have this additional component. Having an additional fixed point for patient positioning provided by the groin post may influence accuracy of component position by prevent motion of the pelvis. However, the groin post on the HANA® table can cause abduction of the proximal femur which may impede appropriate hip fluoroscopic imaging and effect leg length evaluation.

A narrower standard deviation for final anteversion cup placement was found with the use of VELYS™ navigation in comparison to INTELLIJOINT® navigation and conventional technique in our study. In our study, we found a mean deviation of 3.1^0 and 4^0 for target inclination and anteversion using conventional fluoroscopy. Image guided navigation had a mean deviation of 3.2^0 and 2.7^0 in terms of target inclination and anteversion. Imageless navigation was found to have a mean deviation of 3.3^0 and 3.6^0 in terms of target inclination and anteversion. The placement error of final cup position and deviation from surgeon's target zone was non-significant across all three groups. Bosker et al found that conventional freehand placement was only accurate to around 70% of the time in terms of appropriate acetabular inclination. The mean deviation in an experienced consultant's hand is around 4^0 inclination and 5^0

anteversion in comparison to a resident with 6.3^0 and 5.7^0 degrees respectively. [152] Another study reported that the reproducibility of imageless technique in terms of inclination and anteversion had standard deviations of 6.3^O and 9.6^O respectively.[153] Takada et al found that imageless navigation underestimated the cup anteversion during hip replacement with the patient in the supine position. [154] Hasegawa et al reported that abduction errors were around 2.9-3.2 degrees while anteversion errors ranged from 3.7-6.5 degrees in the use of imageless navigation systems in the anterolateral approach. [155] With imageless navigation, the average absolute inclination errors are reported to be between 2.9^0 to 3.7^0 and anteversion between 4.2^0 to 6.8^0.[99,156,157] CT navigation has demonstrated absolute inclination errors between 1.2^0 to 3.2^0 and anteversion between 1.0^0 to 3.3^O.[98,148]

INTELLIJOINT® imageless navigation system has been reported to be within <1mm of leg length and offset and cup position within 1^O in sawbones testing. [158] A cadaveric pelvic study conducted by the Stiel et al found that the use of imageless navigation was more accurate than fluoroscopic guided navigation. This study cited that identifying anatomical landmarks during registration was more challenging in the fluoroscopic navigation group. As this was a cadaveric study, the registration of the anatomical landmarks with a pointer in the imageless system did not require the operator to overcome overlying soft tissue, which may have influenced accuracy. With the use of the pubic tubercle in the APP, the group found an increase of 2-3 degrees anteversion with the image guided navigation. They hypothesized that this may be due to the pubic symphysis being posterior to the pubic tubercle as established in the APP. Stiehl et al hypothesized that inclination error would be higher in the use of imageless navigation as this value is in the coronal plane, colinear with the APP. [159]

It has been recommended that to increase the accuracy of imageless technique, utilising image guided registration with ultrasound or fluoroscopy can be helpful. [160,161] It has been proposed to digitalize the transverse acetabular ligament to improve navigation accuracy for acetabular component position. [162,163] On the contrary, Mihalko et al did not find the use of the TAL improved accuracy over the use of posterior interspinal line.[164] Hakki et al reported the utility of the acetabular center axis, stating comparable accuracy to CT scan and superior to registration of bony landmarks in the APP. [165] It has been demonstrated that BMI >27 with increasing adipose tissue thickness overlying bony landmarks can lead to cup orientation errors due to inaccurate registration of points. [99] Another study demonstrated differences in consistency of soft tissue layers can lead to inaccuracies in registration of APP landmarks. One study demonstrated that a registration error of 4mm leads to approximately 7 degrees error in anteversion and 2 degrees error in inclination. [166] The patient's BMI has been reported to have no significant influence on accuracy of component placement in other studies. Lass et al study found no difference between BMI >27 and BMI <27 groups with use of navigation.[94] Similarly, Takeda et al found equivalent accuracy in component positioning both anteversion and inclination with BMI >25 versus <25.[167]

Our study reinforces that computer assisted navigation does improve accuracy in comparison to conventional techniques. A randomised controlled trial by Verdier et al found that use of navigation lowered the risk of aberrant cup positioning, with improvement in anteversion (0.54; 95% confidence interval, 0.31 -0.91). [168] Ghandi el al reported a metanalysis of three randomized controlled trials, reporting that use of navigation significantly lowered the chance of cups placed as outliers to intended safe zone parameters. [169] Another meta-analysis by Moskal and Capps failed to find a difference between the use of navigation and conventional technique that was statistically significant. The study did observe a tendency for navigated hips to have implants within the safe zone in comparison to conventional techniques. [170] Xu et al. found that in 13 randomised controlled trials, hips using navigation had improved precision of cup position and decreased leg length discrepancy. [102] Liu et al was unable to report a statistically significant difference in mean angles of cup anteversion and inclination and deviation from desired position. The study found that imageless navigation improved accuracy and reduced the likelihood of components being placed outside their target zone in comparison to conventional technique. [171] Beckmann et al demonstrated lower relative risk of outlier cup positioning with use of navigation in their metanalysis (Relative risk, 0.21; 95% confidence interval, 0.13-0.23).[172]

Regarding operative time, we predicted that the use of navigation technology would increase total surgical time. We found that the use of conventional fluoroscopy and VELYS^{TM} image guided navigation were very similar in length of surgery. With the use of the imageless navigation, the set-up requirements include placement of pins on the patient's bony landmarks and registration of anatomical landmarks with digitized pointer. These technical steps are likely responsible for the increased operative time seen with use of imageless navigation technology. [144–146] One of the major concerns in regarding adoption of this technology is the increased operative time leading to potential complications such as periprosthetic infection. Our study found no differences across the three groups in terms of complications. There were no cases with instability within 60 days of surgery in our study. There were no statistically significant differences in peri-prosthetic infection seen in our study. The use of navigation in total hip replacement has been reported to have lower risk dislocation and aseptic revision according to Bohl et al. [83] A review of the Australian Joint Registry has demonstrated that navigation helps to reduce long term revision rates and revision for instability. The use of navigation increased from 1.9% in 2009 to 4.4% in 2019. [173] Montgomery et al found no difference in instability rates between navigated versus non-navigated cohorts. The study found that computer assisted surgery higher rates of periprosthetic fracture and revision in comparison to the conventional cohort. [174] Gausden et al found that the use of navigation led to lower readmission and complication rates. However, there was no significant difference in 90-day revision rates. [175]

Unfortunately, studies looking at long term patient reported outcomes have failed to find a significant improvement with use of navigation technology. One study found that Harris Hip Scores were higher in the navigation arm at 6 weeks however follow up at 1 year demonstrated equivalent outcomes in patient satisfaction, clinical outcomes, and range of motion. [176] Another retrospective study failed to find a difference at 5-7 year follow up with regards to patient outcomes, wear rates, range of motion or periprosthetic bone mineral density. [177] A review of patients having undergone total hip replacement in the anterolateral approach with computer assisted navigation demonstrated no differences in patient outcomes or wear rates at ten years follow up. [178]

The use of robotics has been gaining traction and more surgical centers have started to adopt the technology in the last five years. Robotic technology has been demonstrated to have an influence in component placement. The use of CT navigation with a robotic arm for acetabular cup insertion was found to achieve better accuracy in cup position with anteversion demonstrating significance in comparison to conventional technique. All cases utilizing navigation and robotics were within Lewinnek's safe zone in comparison to 80% of conventional technique. [101] A two-year follow up study found that robotic assisted total hip replacement led to higher acetabular placement accuracy and reduction in dislocations in comparison to traditional hip replacement. Traditional technique led to 5% and 3% rate for early and late dislocation. This was compared to no cases of instability with use of robotics and navigation. [179]

Chapter 7 Conclusion

7.1 Limitations

Our study had a limited follow up period of 60 days and therefore could not report on long term patient reported outcomes or late complications. The focus of our study was centred upon on the accuracy of cup position. We did not include assessment of femoral stem position, leg length and offset in our study.

The study also relied upon intraoperative and post-operative plain radiographs for analysis of cup position. CT remains the gold standard, however we elected not to use this due to cost and radiation risk. The other logistical challenge of utilising CT imaging would be the need for intraoperative CT imaging for comparative analysis with post operative imaging.

In our study, we conducted radiographic follow up intraoperatively and postoperatively at 6 weeks. With this follow-up protocol, we assumed that the cup position once implanted remained in the same position. Based on radiostereometric analysis (RSA) research, cup position may change up to 0.33mm and 0.5-1^0 in angular position at follow up.[180–182] Cup migration may potentially have influenced the accuracy of the measurements conducted in our study.

When looking at our data regarding the cup anteversion, we noted that one of our primary surgeons would override the anteversion readout of the navigation system based upon intraoperative assessment of the cup with concerns for possible coverage of the acetabular component or impingement. The surgeon would potentially increase or decrease the anteversion leading to the cup component falling outside the target anteversion. The study did not include available data regarding surgeon's decision to override cup position during cases due to the retrospective nature of the study. A surgeon's estimated component position recorded during the procedure with notation of any overriding of navigation software would be important in future studies.

7.2 Clinical Relevance

Our goal of this study was to determine if the use of two different navigation systems for total hip cup placement had improved accuracy in comparison to the standard fluoroscopy use in the direct anterior approach. Based on our study, the use of navigation as an additional tool for assessment of cup position does improve placement of component within the surgeon's desired target zone. One of the major differences of our study is the use of narrower target zones specific to the surgeon as opposed to the use of Lewinnek's safe zone which is commonly adopted in other studies. This may explain the discrepancy in accuracy between our study and other published work regarding the accuracy of non-navigated versus navigation guidance in cup placement. With the use of image-guided navigation, estimation of cup anteversion is subject to a degree of error, likely linked with the challenges of obtaining appropriate fluoroscopic imaging and standardised patient positioning. INTELLIJOINT® demonstrated an advantage in lower estimated error of cup position in comparison to VELYS™ and conventional fluoroscopy.

7.3 Further Direction

The future direction should assess long term follow up leading to collection of patient-reported outcome measures, assessment of late complications, and analysis of accuracy of component positioning with the use of robotics in comparison to navigation and conventional technique.

Bibliography

1. Canadian Institute for Health Information. (2022). *Hip and Knee Replacements in Canada: CJRR Annual Report*.
2. Sandiford, N., Kendoff, D., & Muirhead-Allwood, S. (2020). Osteoarthritis of the hip: aetiology, pathophysiology and current aspects of management. *Annals of Joint*, *5*, 8–8. https://doi.org/10.21037/aoj.2019.10.06
3. Callaghan J, Rosenberg J, & Rubash H. (2007). *The Adult Hip* (2nd ed.). Lippincott Williams & Wilkins.
4. Callaghan, J. J., Rubash, H. E., Clohisy, J., Beaule, P., & DellaValle, C. (2015). *The Adult Hip* (3rd Ed., Vols. 1–2). Lippincott Williams & Wilkins.
5. Katz, J. N., Arant, K. R., & Loeser, R. F. (2021). Diagnosis and Treatment of Hip and Knee Osteoarthritis. *JAMA*, *325*(6), 568. https://doi.org/10.1001/jama.2020.22171
6. Tarride, J.-E., Haq, M., O'Reilly, D. J., Bowen, J. M., Xie, F., Dolovich, L., & Goeree, R. (2012). The excess burden of osteoarthritis in the province of Ontario, Canada. *Arthritis & Rheumatism*, *64*(4), 1153–1161. https://doi.org/10.1002/art.33467
7. Murphy, N. J., Eyles, J. P., & Hunter, D. J. (2016). Hip Osteoarthritis: Etiopathogenesis and Implications for Management. In *Advances in Therapy* (Vol. 33, Issue 11, pp. 1921–1946). Springer Healthcare. https://doi.org/10.1007/s12325-016-0409-3
8. Lespasio, M. J., Sultan, A. A., Piuzzi, N. S., Khlopas, A., Husni, M. E., Muschler, G. F., & Mont, M. A. (2018). Hip Osteoarthritis: A Primer. In *The Permanente journal* (Vol. 22). https://doi.org/10.7812/TPP/17-084
9. Fontalis, A., Epinette, J. A., Thaler, M., Zagra, L., Khanduja, V., & Haddad, F. S. (2021). Advances and innovations in total hip arthroplasty. In *SICOT-J* (Vol. 7). EDP Sciences. https://doi.org/10.1051/sicotj/2021025
10. Okafor, L., & Chen, A. F. (2019). Patient satisfaction and total hip arthroplasty: a review. In *Arthroplasty* (Vol. 1, Issue 1). BioMed Central Ltd. https://doi.org/10.1186/s42836-019-0007-3
11. Laupacis, A., Bourne, R., Rorabeck, C., Feeny, D., Wong, C., Tugwell, P., Leslie, K., & Bullas, R. (1993). The effect of elective total hip replacement on health-related quality of life. *The Journal of Bone & Joint Surgery*, *75*(11), 1619–1626. https://doi.org/10.2106/00004623-199311000-00006
12. Liu, X.-W., Zi, Y., Xiang, L.-B., & Wang, Y. (2015). Total hip arthroplasty: areview of advances, advantages and limitations. *International Journal of Clinical and Experimental Medicine*, *8*(1), 27–36.
13. Hawker, G. A., Badley, E. M., Croxford, R., Coyte, P. C., Glazier, R. H., Guan, J., Harvey, B. J., Williams, J. I., & Wright, J. G. (2009). A population-based nested case-control study of the costs of hip and knee replacement surgery. *Medical Care*, *47*(7). https://doi.org/10.1097/MLR.0b013e3181934553
14. Canale, S. T., Beaty, J., & Campbell, W. (2013). *Campbell's operative orthopaedics* (11th ed.). Mosby/Elsevier.
15. Learmonth, I. D., Young, C., & Rorabeck, C. (2007). The operation of the century: total hip replacement. *Lancet (London, England)*, *370*(9597), 1508–1519. https://doi.org/10.1016/S0140-6736(07)60457-7

16. Robinson, P. D., McEwan, J., Adukia, V., & Prabhakar, M. (2018). Osteoarthritis and arthroplasty of the hip and knee. *British Journal of Hospital Medicine*, *79*(4), C54–C59. https://doi.org/10.12968/hmed.2018.79.4.C54
17. Murray, D. (1993). The definition and measurement of acetabular orientation. *The Journal of Bone and Joint Surgery. British Volume*, *75-B*(2), 228–232. https://doi.org/10.1302/0301-620X.75B2.8444942
18. Barsoum, W. K., Patterson, R. W., Higuera, C., Klika, A. K., Krebs, V. E., & Molloy, R. (2007). A computer model of the position of the combined component in the prevention of impingement in total hip replacement. *The Journal of Bone and Joint Surgery. British Volume*, *89-B*(6), 839–845. https://doi.org/10.1302/0301-620X.89B6.18644
19. Abdel, M. P., von Roth, P., Jennings, M. T., Hanssen, A. D., & Pagnano, M. W. (2016). What Safe Zone? The Vast Majority of Dislocated THAs Are Within the Lewinnek Safe Zone for Acetabular Component Position. *Clinical Orthopaedics and Related Research*, *474*(2), 386–391. https://doi.org/10.1007/s11999-015-4432-5
20. Barrack, R. L. (2003). Dislocation After Total Hip Arthroplasty: Implant Design and Orientation. *Journal of the American Academy of Orthopaedic Surgeons*, *11*(2), 89–99. https://doi.org/10.5435/00124635-200303000-00003
21. Dorr, L. D., Malik, A., Dastane, M., & Wan, Z. (2009). Combined Anteversion Technique for Total Hip Arthroplasty. *Clinical Orthopaedics & Related Research*, *467*(1), 119–127. https://doi.org/10.1007/s11999-008-0598-4
22. Sendtner, E., Müller, M., Winkler, R., Wörner, M., Grifka, J., & Renkawitz, T. (2010). Femur first beim Hüftgelenksersatz – Das Konzept der kombinierten Anteversion. *Zeitschrift Für Orthopädie Und Unfallchirurgie*, *148*(02), 185–190. https://doi.org/10.1055/s-0029-1240969
23. Hevesi, M., Wyles, C. C., Rouzrokh, P., Erickson, B. J., Maradit-Kremers, H., Lewallen, D. G., Taunton, M. J., Trousdale, R. T., & Berry, D. J. (n.d.). *Redefining the 3D Topography of the Acetabular Safe Zone A Multivariable Study Evaluating Prosthetic Hip Stability*. https://doi.org/10.2106/JBJS.21.00406
24. Snijders, T. E., Willemsen, K., van Gaalen, S. M., Castelein, R. M., Weinans, H., & de Gast, A. (2019). Lack of consensus on optimal acetabular cup orientation because of variation in assessment methods in total hip arthroplasty: a systematic review. *HIP International*, *29*(1), 41–50. https://doi.org/10.1177/1120700018759306
25. Karachalios, T., Komnos, G., & Koutalos, A. (2018). Total hip arthroplasty: Survival and modes of failure. *EFORT Open Reviews*, *3*(5), 232–239. https://doi.org/10.1302/2058-5241.3.170068
26. DiGioia, A. M., Hafez, M. A., Jaramaz, B., Levison, T. J., & Moody, J. E. (2006). Functional Pelvic Orientation Measured from Lateral Standing and Sitting Radiographs. *Clinical Orthopaedics & Related Research*, *453*, 272–276. https://doi.org/10.1097/01.blo.0000238862.92356.45
27. Lembeck, B., Mueller, O., Reize, P., & Wuelker, N. (2005). Pelvic tilt makes acetabular cup navigation inaccurate. *Acta Orthopaedica*, *76*(4), 517–523. https://doi.org/10.1080/17453670510041501
28. Kelley, T. C., & Swank, M. L. (2009). Role of navigation in total hip arthroplasty. *Journal of Bone and Joint Surgery - Series A*, *91*(SUPPL. 1), 153–158. https://doi.org/10.2106/JBJS.H.01463

29. Davenport, D., & Kavarthapu, V. (2016). Computer navigation of the acetabular component in total hip arthroplasty: A narrative review. *EFORT Open Reviews*, *1*(7), 279–285. https://doi.org/10.1302/2058-5241.1.000050
30. Dargel, J., Oppermann, J., Brüggemann, G. P., & Eysel, P. (2014). Dislocation following total hip replacement. In *Deutsches Arzteblatt International* (Vol. 111, Issues 51–52). https://doi.org/10.3238/arztebl.2014.0884
31. National Joint Registry. (2018). National Joint Registry for England, Wales, Northern Ireland and Isle of Man: 15th Annual Report 2018. *15th Annual Report*, *1821*(December 2017).
32. Ravi, B., Jenkinson, R., Austin, P. C., Croxford, R., Wasserstein, D., Escott, B., Paterson, J. M., Kreder, H., & Hawker, G. A. (2014). Relation between surgeon volume and risk of complications after total hip arthroplasty: Propensity score matched cohort study. *BMJ (Online)*, *348*. https://doi.org/10.1136/bmj.g3284
33. Esposito, C. I., Gladnick, B. P., Lee, Y. yu, Lyman, S., Wright, T. M., Mayman, D. J., & Padgett, D. E. (2015). Cup position alone does not predict risk of dislocation after hip arthroplasty. *Journal of Arthroplasty*, *30*(1). https://doi.org/10.1016/j.arth.2014.07.009
34. Haverkamp, D., Klinkenbijl, M. N., Somford, M. P., Albers, R., & van der Vis, H. M. (2011). Acta Orthopaedica Obesity in total hip arthroplasty-does it really matter? Obesity in total hip arthroplasty-does it really matter? A meta-analysis. *Acta Orthopaedica*, *82*(4).
35. Wagner, E. R., Kamath, A. F., Fruth, K. M., Harmsen, W. S., & Berry, D. J. (2016). Effect of body mass index on complications and reoperations after total hip arthroplasty. *Journal of Bone and Joint Surgery - American Volume*, *98*(3). https://doi.org/10.2106/JBJS.O.00430
36. Buckland, A. J., Puvanesarajah, V., Vigdorchik, J., Schwarzkopf, R., Jain, A., Klineberg, E. O., Hart, R. A., Callaghan, J. J., & Hassanzadeh, H. (2017). Dislocation of a primary total hip arthroplasty is more common in patients with a lumbar spinal fusion. *Bone and Joint Journal*, *99B*(5). https://doi.org/10.1302/0301-620X.99B5.BJJ-2016-0657.R1
37. Putnis, S. E., Wartemberg, G. K., Khan, W. S., & Agarwal, S. (2015). A Literature Review of Total Hip Arthroplasty in Patients with Ankylosing Spondylitis: Perioperative Considerations and Outcome. *The Open Orthopaedics Journal*, *9*(1). https://doi.org/10.2174/1874325001509010483
38. Bergh, C., Fenstad, A. M., Furnes, O., Garellick, G., Havelin, L. I., Overgaard, S., Pedersen, A. B., Mäkelä, K. T., Pulkkinen, P., Mohaddes, M., & Kärrholm, J. (2014). Increased risk of revision in patients with non-traumatic femoral head necrosis. *Acta Orthopaedica*, *85*(1). https://doi.org/10.3109/17453674.2013.874927
39. Danoff, J. R., Bobman, J. T., Cunn, G., Murtaugh, T., Gorroochurn, P., Geller, J. A., & Macaulay, W. (2016). Redefining the Acetabular Component Safe Zone for Posterior Approach Total Hip Arthroplasty. *The Journal of Arthroplasty*, *31*(2), 506–511. https://doi.org/10.1016/j.arth.2015.09.010
40. Lewinnek, G. E., Lewis, J. L., Tarr, R., Compere, C. L., & Zimmerman, J. R. (1978). Dislocations after total hip-replacement arthroplasties. *The Journal of Bone and Joint Surgery. American Volume*, *60*(2), 217–220.
41. Coventry, M. B., Beckenbaugh, R. D., Nolan, D. R., & Ilstrup, D. M. (1974). 2,012 total hip arthroplasties. A study of postoperative course and early complications. *The Journal of Bone and Joint Surgery. American Volume*, *56*(2), 273–284.

42. McCollum, D. E., & Gray, W. J. (1990). Dislocation after total hip arthroplasty. Causes and prevention. *Clinical Orthopaedics and Related Research*, *261*, 159–170.
43. Biedermann, R., Tonin, A., Krismer, M., Rachbauer, F., Eibl, G., & Stöckl, B. (2005). Reducing the risk of dislocation after total hip arthroplasty THE EFFECT OF ORIENTATION OF THE ACETABULAR COMPONENT. *THE JOURNAL OF BONE AND JOINT SURGERY*. https://doi.org/10.1302/0301-620X.87B6
44. Nishii, T., Sugano, N., Miki, H., Koyama, T., Takao, M., & Yoshikawa, H. (2004). Influence of component positions on dislocation. *The Journal of Arthroplasty*, *19*(2), 162–166. https://doi.org/10.1016/j.arth.2003.09.005
45. Robinson, R. P., Simonian, P. T., Gradisar, I. M., & Ching, R. P. (1997). Joint motion and surface contact area related to component position in total hip arthroplasty. *The Journal of Bone and Joint Surgery. British Volume*, *79*(1), 140–146. https://doi.org/10.1302/0301-620x.79b1.6842
46. Little, N. J., Busch, C. A., Gallagher, J. A., Rorabeck, C. H., & Bourne, R. B. (2009). Acetabular polyethylene wear and acetabular inclination and femoral offset. *Clinical Orthopaedics and Related Research*, *467*(11), 2895–2900. https://doi.org/10.1007/s11999-009-0845-3
47. PATIL, S., BERGULA, A., CHEN, P. C., COLWELL, C. W., & D'LIMA, D. D. (2003). POLYETHYLENE WEAR AND ACETABULAR COMPONENT ORIENTATION. *The Journal of Bone and Joint Surgery-American Volume*, *85*, 56–63. https://doi.org/10.2106/00004623-200300004-00007
48. Kennedy, J. G., Rogers, W. B., Soffe, K. E., Sullivan, R. J., Griffen, D. G., & Sheehan, L. J. (1998). Effect of acetabular component orientation on recurrent dislocation, pelvic osteolysis, polyethylene wear, and component migration. *The Journal of Arthroplasty*, *13*(5), 530–534. https://doi.org/10.1016/S0883-5403(98)90052-3
49. del Schutte, H., Lipman, A. J., Bannar, S. M., Livermore, J. T., Ilstrup, D., & Morrey, B. F. (1998). Effects of acetabular abduction on cup wear rates in total hip arthroplasty. *The Journal of Arthroplasty*, *13*(6), 621–626. https://doi.org/10.1016/S0883-5403(98)80003-X
50. Goyal, P., Howard, J. L., Yuan, X., Teeter, M. G., & Lanting, B. A. (2017). Effect of Acetabular Position on Polyethylene Liner Wear Measured Using Simultaneous Biplanar Acquisition. *Journal of Arthroplasty*, *32*(5). https://doi.org/10.1016/j.arth.2016.11.057
51. Crowninshield, R. D., Maloney, W. J., Wentz, D. H., Humphrey, S. M., & Blanchard, C. R. (2004). Biomechanics of large femoral heads: what they do and don't do. *Clinical Orthopaedics and Related Research*, *429*, 102–107.
52. Waewsawangwong, W., & Goodman, S. B. (2012). Unexpected Failure of Highly Cross-Linked Polyethylene Acetabular Liner. *The Journal of Arthroplasty*, *27*(2), 323.e1-323.e4. https://doi.org/10.1016/j.arth.2011.04.010
53. Tower, S. S., Currier, J. H., Currier, B. H., Lyford, K. A., van Citters, D. W., & Mayor, M. B. (2007). Rim Cracking of the Cross-Linked Longevity Polyethylene Acetabular Liner After Total Hip Arthroplasty. *The Journal of Bone & Joint Surgery*, *89*(10), 2212–2217. https://doi.org/10.2106/JBJS.F.00758
54. de Haan, R., Campbell, P. A., Su, E. P., & de Smet, K. A. (2008). Revision of metal-on-metal resurfacing arthroplasty of the hip. *The Journal of Bone and Joint Surgery. British Volume*, *90-B*(9), 1158–1163. https://doi.org/10.1302/0301-620X.90B9.19891

55. Sexton, S. A., Yeung, E., Jackson, M. P., Rajaratnam, S., Martell, J. M., Walter, W. L., Zicat, B. A., & Walter, W. K. (2011). The role of patient factors and implant position in squeaking of ceramic-on-ceramic total hip replacements. *The Journal of Bone and Joint Surgery. British Volume*, *93-B*(4), 439–442. https://doi.org/10.1302/0301-620X.93B4.25707
56. Griffin, W. L., Nanson, C. J., Springer, B. D., Davies, M. A., & Fehring, T. K. (2010). Reduced articular surface of one-piece cups: a cause of runaway wear and early failure. *Clinical Orthopaedics and Related Research*, *468*(9), 2328–2332. https://doi.org/10.1007/s11999-010-1383-8
57. Kummer, F. J., Shah, S., Iyer, S., & DiCesare, P. E. (1999). The effect of acetabular cup orientations on limiting hip rotation. *The Journal of Arthroplasty*, *14*(4), 509–513. https://doi.org/10.1016/S0883-5403(99)90110-9
58. D'LIMA, D. D., URQUHART, A. G., BUEHLER, K. O., WALKER, R. H., & COLWELL, C. W. (2000). The Effect of the Orientation of the Acetabular and Femoral Components on the Range of Motion of the Hip at Different Head-Neck Ratios*. *The Journal of Bone and Joint Surgery-American Volume*, *82*(3), 315–321. https://doi.org/10.2106/00004623-200003000-00003
59. Trousdale, R. T., Cabanela, M. E., & Berry, D. J. (1995). Anterior iliopsoas impingement after total hip arthroplasty. *The Journal of Arthroplasty*, *10*(4), 546–549. https://doi.org/10.1016/S0883-5403(05)80160-3
60. Robinson, A. (1918). *ed. Cunningham's Text-book of Anatomy 5th Ed*. William Wood and Company.
61. Callanan, M. C., Jarrett, B., Bragdon, C. R., Zurakowski, D., Rubash, H. E., Freiberg, A. A., & Malchau, H. (2011). The John Charnley Award: risk factors for cup malpositioning: quality improvement through a joint registry at a tertiary hospital. *Clinical Orthopaedics and Related Research*, *469*(2), 319–329. https://doi.org/10.1007/s11999-010-1487-1
62. Lin, F., Lim, D., Wixson, R. L., Milos, S., Hendrix, R. W., & Makhsous, M. (2011). Limitations of Imageless Computer-Assisted Navigation for Total Hip Arthroplasty. *Journal of Arthroplasty*, *26*(4), 596–605. https://doi.org/10.1016/j.arth.2010.05.027
63. Maruyama, M., Feinberg, J. R., Capello, W. N., & D'Antonio, J. A. (2001). The Frank Stinchfield Award: Morphologic features of the acetabulum and femur: anteversion angle and implant positioning. *Clinical Orthopaedics and Related Research*, *393*, 52–65.
64. Sotereanos, N. G., Miller, M. C., Smith, B., Hube, R., Sewecke, J. J., & Wohlrab, D. (2006). Using Intraoperative Pelvic Landmarks for Acetabular Component Placement in Total Hip Arthroplasty. *The Journal of Arthroplasty*, *21*(6), 832–840. https://doi.org/10.1016/j.arth.2005.12.001
65. Epstein, N. J., Woolson, S. T., & Giori, N. J. (2011). Acetabular component positioning using the transverse acetabular ligament: can you find it and does it help? *Clinical Orthopaedics and Related Research*, *469*(2), 412–416. https://doi.org/10.1007/s11999-010-1523-1
66. Archbold, H. A. P., Slomczykowski, M., Crone, M., Eckman, K., Jaramaz, B., & Beverland, D. E. (2008). The relationship of the orientation of the transverse acetabular ligament and acetabular labrum to the suggested safe zones of cup positioning in total hip arthroplasty. *Hip International*, *18*(1), 1–6. https://doi.org/10.5301/HIP.2008.1755
67. Woo, R. Y., & Morrey, B. F. (1982). Dislocations after total hip arthroplasty. *The Journal of Bone and Joint Surgery. American Volume*, *64*(9), 1295–1306.

68. DiGioia, A. M., Jaramaz, B., Plakseychuk, A. Y., Moody, J. E., Nikou, C., LaBarca, R. S., Levison, T. J., & Picard, F. (2002). Comparison of a mechanical acetabular alignment guide with computer placement of the socket. *The Journal of Arthroplasty*, *17*(3), 359–364. https://doi.org/10.1054/arth.2002.30411
69. Saxler, G., Marx, A., Vandevelde, D., Langlotz, U., Tannast, M., Wiese, M., Michaelis, U., Kemper, G., Grützner, P. A., Steffen, R., von Knoch, M., Holland-Letz, T., & Bernsmann, K. (2004). The accuracy of free-hand cup positioning - a CT based measurement of cup placement in 105 total hip arthroplasties. *International Orthopaedics*, *28*(4), 198–201. https://doi.org/10.1007/s00264-004-0542-5
70. Hassan, D. M., Johnston, G. H., Dust, W. N., Watson, G., & Dolovich, A. T. (1998). Accuracy of intraoperative assessment of acetabular prosthesis placement. *The Journal of Arthroplasty*, *13*(1), 80–84. https://doi.org/10.1016/s0883-5403(98)90079-1
71. Grammatopoulos, G., Gofton, W., Cochran, M., Dobransky, J., Carli, A., Abdelbary, H., Gill, H. S., & Beaulé, P. E. (2018). Pelvic positioning in the supine position leads to more consistent orientation of the acetabular component after total hip arthroplasty. *Bone and Joint Journal*, *100B*(10), 1280–1288. https://doi.org/10.1302/0301-620X.100B10.BJJ-2018-0134.R1
72. DiGioia, A. M., Jaramaz, B., Blackwell, M., Simon, D. A., Morgan, F., Moody, J. E., Nikou, C., Colgan, B. D., Aston, C. A., Labarca, R. S., Kischell, E., & Kanade, T. (1998). Image Guided Navigation System to Measure Intraoperatively Acetabular Implant Alignment. *Clinical Orthopaedics and Related Research*, *355*, 8–22. https://doi.org/10.1097/00003086-199810000-00003
73. Goyal, P., Lau, A., McCalden, R., Teeter, M. G., Howard, J. L., & Lanting, B. A. (2016). Accuracy of the modified Hardinge approach in acetabular positioning. *Canadian Journal of Surgery*, *59*(4). https://doi.org/10.1503/cjs.011415
74. Rathod, P. A., Bhalla, S., Deshmukh, A. J., & Rodriguez, J. A. (2014). Does Fluoroscopy With Anterior Hip Arthoplasty Decrease Acetabular Cup Variability Compared With a Nonguided Posterior Approach? *Clinical Orthopaedics & Related Research*, *472*(6), 1877–1885. https://doi.org/10.1007/s11999-014-3512-2
75. Beamer, B. S., Morgan, J. H., Barr, C., Weaver, M. J., & Vrahas, M. S. (2014). Does Fluoroscopy Improve Acetabular Component Placement in Total Hip Arthroplasty? *Clinical Orthopaedics and Related Research®*, *472*(12), 3953–3962. https://doi.org/10.1007/s11999-014-3944-8
76. Delagrammaticas, D. E., Ochenjele, G., Rosenthal, B. D., Assenmacher, B., Manning, D. W., & Stover, M. D. (2020). Intraoperative evaluation of acetabular cup position during anterior approach total hip arthroplasty: are we accurately interpreting? *HIP International*, *30*(1), 40–47. https://doi.org/10.1177/1120700019868665
77. Wasterlain, A. S., Buza, J. A., Thakkar, S. C., Schwarzkopf, R., & Vigdorchik, J. (2017). Navigation and robotics in total hip arthroplasty. *JBJS Reviews*, *5*(3). https://doi.org/10.2106/JBJS.RVW.16.00046
78. Ecker, T. M., & Murphy, S. B. (2007). Application of surgical navigation to total hip arthroplasty. *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine*, *221*(7), 699–712. https://doi.org/10.1243/09544119JEIM271

79. Aoude, A. A., Aldebeyan, S. A., Nooh, A., Weber, M. H., & Tanzer, M. (2016). Thirty-Day Complications of Conventional and Computer-Assisted Total Knee and Total Hip Arthroplasty: Analysis of 103,855 Patients in the American College of Surgeons National Surgical Quality Improvement Program Database. *The Journal of Arthroplasty*, *31*(8), 1674–1679. https://doi.org/10.1016/j.arth.2016.01.042
80. Boylan, M., Suchman, K., Vigdorchik, J., Slover, J., & Bosco, J. (2018). Technology-Assisted Hip and Knee Arthroplasties: An Analysis of Utilization Trends. *The Journal of Arthroplasty*, *33*(4), 1019–1023. https://doi.org/10.1016/J.ARTH.2017.11.033
81. Chaudhry, F. A., Ismail, S. Z., & Davis, E. T. (2018). A new system of computer-assisted navigation leading to reduction in operating time in uncemented total hip replacement in a matched population. *European Journal of Orthopaedic Surgery and Traumatology*, *28*(4), 645–648. https://doi.org/10.1007/s00590-018-2133-y
82. Valsamis, E. M., Ricketts, D., Hussain, A., & Jenabzadeh, A. R. (2018). Imageless navigation total hip arthroplasty - An evaluation of operative time. *SICOT-J*, *4*. https://doi.org/10.1051/sicotj/2018016
83. Bohl, D. D., Nolte, M. T., Ong, K., Lau, E., Calkins, T. E., & della Valle, C. J. (2019). Computer-assisted navigation is associated with reductions in the rates of dislocation and acetabular component revision following primary total hip arthroplasty. *Journal of Bone and Joint Surgery - American Volume*, *101*(3), 250–256. https://doi.org/10.2106/JBJS.18.00108
84. Brown, M. L., Reed, J. D., & Drinkwater, C. J. (2014). Imageless Computer-Assisted versus Conventional Total Hip Arthroplasty: One Surgeon’s Initial Experience. *The Journal of Arthroplasty*, *29*(5), 1015–1020. https://doi.org/10.1016/j.arth.2013.10.007
85. Deep, K., Shankar, S., & Mahendra, A. (2017). Computer assisted navigation in total knee and hip arthroplasty. *SICOT-J*, *3*, 50. https://doi.org/10.1051/sicotj/2017034
86. Chang, J.-D., Kim, I.-S., Bhardwaj, A. M., & Badami, R. N. (2017). The Evolution of Computer-Assisted Total Hip Arthroplasty and Relevant Applications. *Hip & Pelvis*, *29*(1), 1. https://doi.org/10.5371/hp.2017.29.1.1
87. Sugano, N. (2013). Computer-Assisted Orthopaedic Surgery and Robotic Surgery in Total Hip Arthroplasty. *Clinics in Orthopedic Surgery*, *5*(1), 1. https://doi.org/10.4055/cios.2013.5.1.1
88. Gross, A. E., Safir, O. A., Kuzyk, P. R. T., Sculco, P. K., Wolfstadt, J., Girardi, B. L., Fichman, S. G., & Muir, J. M. (2018). Optimizing leg length and cup position: A surgical navigation tool. *Seminars in Arthroplasty*, *29*(3), 157–160. https://doi.org/10.1053/j.sart.2019.02.008
89. Ogawa, H., Kurosaka, K., Sato, A., Hirasawa, N., Matsubara, M., & Tsukada, S. (2020). Does An Augmented Reality-based Portable Navigation System Improve the Accuracy of Acetabular Component Orientation during THA? A Randomized Controlled Trial. *Clinical Orthopaedics and Related Research*, *478*(5). https://doi.org/10.1097/CORR.0000000000001083
90. Richolt, J. A., Effenberger, H., & Rittmeister, M. E. (2005). How does soft tissue distribution affect anteversion accuracy of the palpation procedure in image-free acetabular cup navigation? An ultrasonographic assessment. *Computer Aided Surgery*, *10*(2), 87–92. https://doi.org/10.3109/10929080500229447

91. Dorr, L. D., Hishiki, Y., Wan, Z., Newton, D., & Yun, A. (2005). Development of imageless computer navigation for acetabular component position in total hip replacement. *The Iowa Orthopaedic Journal*, *25*, 1–9.
92. Barbier, O., Skalli, W., Mainard, L., Mainard, D., & Computer Assisted Orthopedic Surgery–France (CAOS-France). (2014). The reliability of the anterior pelvic plane for computer navigated acetabular component placement during total hip arthroplasty: prospective study with the EOS imaging system. *Orthopaedics & Traumatology, Surgery & Research : OTSR*, *100*(6 Suppl), S287-91. https://doi.org/10.1016/j.otsr.2014.07.003
93. Dorr, L. D., Malik, A., Wan, Z., Long, W. T., & Harris, M. (2007). Precision and bias of imageless computer navigation and surgeon estimates for acetabular component position. *Clinical Orthopaedics and Related Research*, *465*. https://doi.org/10.1097/BLO.0b013e3181560c51
94. Lass, R., Olischar, B., Kubista, B., Waldhoer, T., Giurea, A., & Windhager, R. (2020). Total Hip Arthroplasty Using Imageless Computer-Assisted Navigation—2-Year Follow-Up of a Prospective Randomized Study. *Journal of Clinical Medicine*, *9*(6), 1620. https://doi.org/10.3390/jcm9061620
95. Suksathien, Y., Suksathien, R., & Chaiwirattana, P. (2014). Acetabular cup placement in navigated and non-navigated total hip arthroplasty (THA): results of two consecutive series using a cementless short stem. *Journal of the Medical Association of Thailand = Chotmaihet Thangphaet*, *97*(6), 629–634.
96. Singer, G. (2005). Occupational Radiation Exposure to the Surgeon. *Journal of the American Academy of Orthopaedic Surgeons*, *13*(1), 69–76. https://doi.org/10.5435/00124635-200501000-00009
97. Masonis, J., Thompson, C., & Odum, S. (2008). Safe and accurate: learning the direct anterior total hip arthroplasty. *Orthopedics*, *31*(12 Suppl 2).
98. Kalteis, T., Handel, M., Bäthis, H., Perlick, L., Tingart, M., & Grifka, J. (2006). Imageless navigation for insertion of the acetabular component in total hip arthroplasty. Is it accurate as CT-based navigation? *Journal of Bone and Joint Surgery - Series B*, *88*(2). https://doi.org/10.1302/0301-620X.88B2.17163
99. Parratte, S., & Argenson, J.-N. A. (2007). Validation and usefulness of a computer-assisted cup-positioning system in total hip arthroplasty. A prospective, randomized, controlled study. *The Journal of Bone and Joint Surgery. American Volume*, *89*(3), 494–499. https://doi.org/10.2106/JBJS.F.00529
100. Kabata, T., Kajino, Y., Hasegawa, K., Inoue, D., Yamamoto, T., Takagi, T., Ohmori, T., & Tsuchiya, H. (2018). Early dislocation rate in computer navigation-assisted primary total hip arthroplasty through a posterior approach. *Bone Joint J*, *99*(4).
101. Domb, B. G., el Bitar, Y. F., Sadik, A. Y., Stake, C. E., & Botser, I. B. (2014). Comparison of robotic-assisted and conventional acetabular cup placement in THA: A matched-pair controlled study hip. *Clinical Orthopaedics and Related Research*, *472*(1). https://doi.org/10.1007/s11999-013-3253-7
102. Xu, K., Li, Y., Zhang, H., Wang, C., Xu, Y., & Li, Z. (2014). Computer navigation in total hip arthroplasty: A meta-analysis of randomized controlled trials. *International Journal of Surgery*, *12*(5), 528–533. https://doi.org/10.1016/j.ijsu.2014.02.014
103. Moskal, J. T., & Capps, S. G. (2010). Improving the Accuracy of Acetabular Component Orientation: Avoiding Malposition. *American Academy of*

Orthopaedic Surgeon, *18*(5), 286–296. https://doi.org/10.5435/00124635-201005000-00005

104. Li, Y. L., Jia, J., Wu, Q., Ning, G. Z., Wu, Q. L., & Feng, S. Q. (2014). Evidence-based computer-navigated total hip arthroplasty: An updated analysis of randomized controlled trials. *European Journal of Orthopaedic Surgery and Traumatology*, *24*(4). https://doi.org/10.1007/s00590-013-1222-1
105. Inoue, D., Kabata, T., Kajino, Y., Ohmori, T., Ueno, T., Taga, T., Takagi, T., Yoshitani, J., Ueoka, K., Yamamuro, Y., & Tsuchiya, H. (2020). Postsurgical infection from using a computed tomography-based hip navigation system during total hip arthroplasty. *European Journal of Orthopaedic Surgery and Traumatology*, *30*(6). https://doi.org/10.1007/s00590-020-02676-5
106. Meermans, G., Konan, S., Das, R., Volpin, A., & Haddad, F. S. (2017). The direct anterior approach in total hip arthroplasty. *The Bone & Joint Journal*, *99-B*(6), 732–740. https://doi.org/10.1302/0301-620X.99B6.38053
107. Burnett, S. (n.d.). *Total hip arthroplasty: Techniques and results*.
108. Meneghini, R. M., Pagnano, M. W., Trousdale, R. T., & Hozack, W. J. (2006). Muscle damage during MIS total hip arthroplasty: Smith-peterson versus posterior approach. *Clinical Orthopaedics and Related Research*, *453*. https://doi.org/10.1097/01.blo.0000238859.46615.34
109. Gershkovich, G. E., Tiedeken, N. C., Hampton, D., Budacki, R., Samuel, S. P., & Saing, M. (2016). A Comparison of Three C-Arm Draping Techniques to Minimize Contamination of the Surgical Field. *Journal of Orthopaedic Trauma*, *30*(10), e351–e356. https://doi.org/10.1097/BOT.0000000000000619
110. Pomeroy, C. L., Mason, J. B., Fehring, T. K., Masonis, J. L., & Curtin, B. M. (2016). Radiation Exposure During Fluoro-Assisted Direct Anterior Total Hip Arthroplasty. *The Journal of Arthroplasty*, *31*(8), 1742–1745. https://doi.org/10.1016/j.arth.2016.01.031
111. Ross, A. M., Segal, J., Borenstein, D., Jenkins, E., & Cho, S. (1997). Prevalence of Spinal Disc Disease Among Interventional Cardiologists. *The American Journal of Cardiology*, *79*(1), 68–70. https://doi.org/10.1016/S0002-9149(96)00678-9
112. Curtin, B. M., Armstrong, L. C., Bucker, B. T., Odum, S. M., & Jiranek, W. A. (2016). Patient Radiation Exposure During Fluoro-Assisted Direct Anterior Approach Total Hip Arthroplasty. *The Journal of Arthroplasty*, *31*(6), 1218–1221. https://doi.org/10.1016/j.arth.2015.12.012
113. D'Arrigo, C., Speranza, A., Monaco, E., Carcangiu, A., & Ferretti, A. (2009). Learning curve in tissue sparing total hip replacement: comparison between different approaches. *Journal of Orthopaedics and Traumatology : Official Journal of the Italian Society of Orthopaedics and Traumatology*, *10*(1), 47–54. https://doi.org/10.1007/s10195-008-0043-1
114. Parvizi, J., Rasouli, M. R., Jaberi, M., Chevrollier, G., Vizzi, S., Sharkey, P. F., & Hozack, W. J. (2013). Does the surgical approach in one stage bilateral total hip arthroplasty affect blood loss? *International Orthopaedics*, *37*(12), 2357–2362. https://doi.org/10.1007/s00264-013-2093-0
115. Higgins, B. T., Barlow, D. R., Heagerty, N. E., & Lin, T. J. (2015). Anterior vs. Posterior Approach for Total Hip Arthroplasty, a Systematic Review and Meta-analysis. *The Journal of Arthroplasty*, *30*(3), 419–434. https://doi.org/10.1016/j.arth.2014.10.020
116. Free, M. D., Owen, D. H., Agius, P. A., Pascoe, E. M., & Harvie, P. (2018). Direct Anterior Approach Total Hip Arthroplasty: An Adjunct to an Enhanced

Recovery Pathway: Outcomes and Learning Curve Effects in Surgeons Transitioning From Other Surgical Approaches. *The Journal of Arthroplasty*, *33*(11), 3490–3495. https://doi.org/10.1016/j.arth.2018.06.033

117. Galakatos, G. R. (2018). Direct Anterior Total Hip Arthroplasty. *Missouri Medicine*, *115*(6), 537–541.
118. Alecci, V., Valente, M., Crucil, M., Minerva, M., Pellegrino, C.-M., & Sabbadini, D. D. (2011). Comparison of primary total hip replacements performed with a direct anterior approach versus the standard lateral approach: perioperative findings. *Journal of Orthopaedics and Traumatology*, *12*(3), 123–129. https://doi.org/10.1007/s10195-011-0144-0
119. Restrepo, C., Parvizi, J., Pour, A. E., & Hozack, W. J. (2010). Prospective Randomized Study of Two Surgical Approaches for Total Hip Arthroplasty. *Journal of Arthroplasty*, *25*(5). https://doi.org/10.1016/j.arth.2010.02.002
120. Siljander, M. P., Whaley, J. D., Koueiter, D. M., Alsaleh, M., & Karadsheh, M. S. (2020). Length of Stay, Discharge Disposition, and 90-Day Complications and Revisions Following Primary Total Hip Arthroplasty: A Comparison of the Direct Anterior, Posterolateral, and Direct Superior Approaches. *The Journal of Arthroplasty*, *35*(6), 1658–1661. https://doi.org/10.1016/j.arth.2020.01.082
121. O'Connor, C. M., Anoushiravani, A. A., Acosta, E., Davidovitch, R. I., & Tetreault, M. W. (2021). Direct Anterior Approach Total Hip Arthroplasty Is Not Associated with Increased Infection Rates: A Systematic Review and Meta-Analysis. *JBJS Reviews*, *9*(1), e20.00047. https://doi.org/10.2106/JBJS.RVW.20.00047
122. Fleischman, A. N., Tarabichi, M., Magner, Z., Parvizi, J., & Rothman, R. H. (2019). Mechanical Complications Following Total Hip Arthroplasty Based on Surgical Approach: A Large, Single-Institution Cohort Study. *The Journal of Arthroplasty*, *34*(6), 1255–1260. https://doi.org/10.1016/j.arth.2019.02.029
123. Tamaki, T., Oinuma, K., Miura, Y., Higashi, H., Kaneyama, R., & Shiratsuchi, H. (2016). Epidemiology of Dislocation Following Direct Anterior Total Hip Arthroplasty: A Minimum 5-Year Follow-Up Study. *The Journal of Arthroplasty*, *31*(12), 2886–2888. https://doi.org/10.1016/j.arth.2016.05.042
124. Lee, G.-C., & Marconi, D. (2015). Complications Following Direct Anterior Hip Procedures: Costs to Both Patients and Surgeons. *The Journal of Arthroplasty*, *30*(9), 98–101. https://doi.org/10.1016/j.arth.2015.03.043
125. Kotwal, R. S., Ganapathi, M., John, A., Maheson, M., & Jones, S. A. (2009). Outcome of treatment for dislocation after primary total hip replacement. *Journal of Bone and Joint Surgery - Series B*, *91*(3). https://doi.org/10.1302/0301-620X.91B3.21274
126. Parvizi, J., Benson, J. R., & Muir, J. M. (2018). A new mini-navigation tool allows accurate component placement during anterior total hip arthroplasty. *Medical Devices: Evidence and Research*, *11*, 95–104. https://doi.org/10.2147/MDER.S151835
127. Free, M. D., Barnes, I., Hutchinson, M., & Harvie, P. (2021). Preoperative radiographs to predict component malposition in direct anterior approach total hip arthroplasty. *HIP International*. https://doi.org/10.1177/11207000211037596
128. Matta, J. M., Shahrdar, C., & Ferguson, T. (2005). Single-incision Anterior Approach for Total Hip Arthroplasty on an Orthopaedic Table. *Clinical Orthopaedics and Related Research*, *441*(NA;), 115–124. https://doi.org/10.1097/01.blo.0000194309.70518.cb

129. Lin, T. J., Bendich, I., Ha, A. S., Keeney, B. J., Moschetti, W. E., & Tomek, I. M. (2017). A Comparison of Radiographic Outcomes After Total Hip Arthroplasty Between the Posterior Approach and Direct Anterior Approach With Intraoperative Fluoroscopy. *The Journal of Arthroplasty*, *32*(2), 616–623. https://doi.org/10.1016/j.arth.2016.07.046
130. Nogler, M., Mayr, E., Krismer, M., & Thaler, M. (2008). Reduced variability in cup positioning: the direct anterior surgical approach using navigation. *Acta Orthopaedica*, *79*(6), 789–793. https://doi.org/10.1080/17453670810016867
131. Debi, R., Slamowicz, E., Cohen, O., Elbaz, A., Lubovsky, O., Lakstein, D., Tan, Z., & Atoun, E. (2018). Acetabular cup orientation and postoperative leg length discrepancy in patients undergoing elective total hip arthroplasty via a direct anterior and anterolateral approaches. *BMC Musculoskeletal Disorders*, *19*(1), 188. https://doi.org/10.1186/s12891-018-2097-4
132. Liaw, C. K., Hou, S. M., Yang, R. sen, Wu, T. Y., & Fuh, C. S. (2006). A new tool for measuring cup orientation in total hip arthroplasties from plain radiographs. *Clinical Orthopaedics and Related Research*, *451*. https://doi.org/10.1097/01.blo.0000223988.41776.fa
133. Pradhan, R. (1999). Planar anteversion of the acetabular cup as determined from plain anteroposterior radiographs. *Journal of Bone and Joint Surgery - Series B*, *81*(3). https://doi.org/10.1302/0301-620X.81B3.9067
134. Lee, G. C., Lee, S. H., Kang, S. W., Park, H. S., & Jo, S. (2019). Accuracy of planar anteversion measurements using anteroposterior radiographs. *BMC Musculoskeletal Disorders*, *20*(1), 586. https://doi.org/10.1186/s12891-019-2979-0
135. Seagrave, K. G., Troelsen, A., Malchau, H., Husted, H., & Gromov, K. (2017). Acetabular cup position and risk of dislocation in primary total hip arthroplasty. *Acta Orthopaedica*, *88*(1), 10–17. https://doi.org/10.1080/17453674.2016.1251255
136. Tannast, M., Langlotz, U., Siebenrock, K.-A., Wiese, M., Bernsmann, K., & Langlotz, F. (2005). Anatomic Referencing of Cup Orientation in Total Hip Arthroplasty. *Clinical Orthopaedics and Related Research*, *NA;*(436), 144–150. https://doi.org/10.1097/01.blo.0000157657.22894.29
137. Widmer, K.-H. (2004). A simplified method to determine acetabular cup anteversion from plain radiographs. *The Journal of Arthroplasty*, *19*(3), 387–390. https://doi.org/10.1016/j.arth.2003.10.016
138. Herrlin, K., Pettersson, H., & Selvik, G. (n.d.). Comparison of two- and three-dimensional methods for assessment of orientation of the total hip prosthesis. *Acta Radiologica (Stockholm, Sweden : 1987)*, *29*(3), 357–361.
139. Esposito, C. I., Miller, T. T., Lipman, J. D., Carroll, K. M., Padgett, D. E., Mayman, D. J., & Jerabek, S. A. (2020). Biplanar Low-Dose Radiography Is Accurate for Measuring Combined Anteversion After Total Hip Arthroplasty. *HSS Journal*, *16*(1), 23–29. https://doi.org/10.1007/s11420-018-09659-7
140. Lahy, J., Stevens, J., McKenzie, D., & de Steiger, R. (2017). The reliability of measuring acetabular component position on radiographs using everyday diagnostic imaging software. *Journal of Orthopaedic Surgery*, *25*(2), 230949901771895. https://doi.org/10.1177/2309499017718953
141. Lu, M., Zhou, Y.-X., Du, H., Zhang, J., & Liu, J. (2013). Reliability and Validity of Measuring Acetabular Component Orientation by Plain Anteroposterior Radiographs. *Clinical Orthopaedics & Related Research*, *471*(9), 2987–2994. https://doi.org/10.1007/s11999-013-3021-8

142. Jennings, J. D., Iorio, J., Kleiner, M. T., Gaughan, J. P., & Star, A. M. (2015). Intraoperative Fluoroscopy Improves Component Position During Anterior Hip Arthroplasty. *Orthopedics*, *38*(11). https://doi.org/10.3928/01477447-20151020-04
143. Tannast, M., Langlotz, F., Kubiak-Langer, M., Langlotz, U., & Siebenrock, K.-A. (2005). Accuracy and potential pitfalls of fluoroscopy-guided acetabular cup placement. *Computer Aided Surgery*, *10*(5–6), 329–336. https://doi.org/10.3109/10929080500379481
144. Stiehl, J. B., Heck, D. A., & Lazzeri, M. (2005). Accuracy of acetabular component positioning with a fluoroscopically referenced CAOS system. *Computer Aided Surgery*, *10*(5–6), 321–327. https://doi.org/10.3109/10929080500379499
145. Hartford, J. M., & Bellino, M. J. (2017). The Learning Curve for the Direct Anterior Approach for Total Hip Arthroplasty: A Single Surgeon's First 500 Cases. *HIP International*, *27*(5), 483–488. https://doi.org/10.5301/hipint.5000488
146. Jang, E. S., Lin, J. D., Shah, R. P., Geller, J. A., & Cooper, H. J. (2018). The effect of c-arm tilt on accuracy of intraoperative fluoroscopy in assessing acetabular component position during direct anterior approach for hip arthroplasty. *Journal of Orthopaedics*, *15*(2), 447–449. https://doi.org/10.1016/j.jor.2018.03.036
147. Shah, S. M., Walter, W. L., & Ngo, J. (2017). Is the pelvis stable during supine total hip arthroplasty? *Acta Orthopaedica Belgica*, *83*(1), 81–86.
148. Tetsunaga, T., Yamada, K., Tetsunaga, T., Sanki, T., Kawamura, Y., & Ozaki, T. (2020). An accelerometer-based navigation system provides acetabular cup orientation accuracy comparable to that of computed tomography-based navigation during total hip arthroplasty in the supine position. *Journal of Orthopaedic Surgery and Research*, *15*(1). https://doi.org/10.1186/s13018-020-01673-y
149. Babisch, J. W., Layher, F., & Amiot, L.-P. (2008). The Rationale for Tilt-Adjusted Acetabular Cup Navigation. *The Journal of Bone & Joint Surgery*, *90*(2), 357–365. https://doi.org/10.2106/JBJS.F.00628
150. Eilander, W., Harris, S. J., Henkus, H. E., Cobb, J. P., & Hogervorst, T. (2013). Functional acetabular component position with supine total hip replacement. *The Bone & Joint Journal*, *95-B*(10), 1326–1331. https://doi.org/10.1302/0301-620X.95B10.31446
151. Wan, Z., Malik, A., Jaramaz, B., Chao, L., & Dorr, L. D. (2009). Imaging and Navigation Measurement of Acetabular Component Position in THA. *Clinical Orthopaedics & Related Research*, *467*(1), 32–42. https://doi.org/10.1007/s11999-008-0597-5
152. Bosker, B. H., Verheyen, C. C. P. M., Horstmann, W. G., & Tulp, N. J. A. (2007). Poor accuracy of freehand cup positioning during total hip arthroplasty. *Archives of Orthopaedic and Trauma Surgery*, *127*(5), 375–379. https://doi.org/10.1007/s00402-007-0294-y
153. Spencer, J. M. F., Day, R. E., Sloan, K. E., & Beaver, R. J. (2006). Computer navigation of the acetabular component. *The Journal of Bone and Joint Surgery. British Volume*, *88-B*(7), 972–975. https://doi.org/10.1302/0301-620X.88B7.17468
154. Takada, R., Jinno, T., Miyatake, K., Hirao, M., Yoshii, T., & Okawa, A. (2020). Portable imageless navigation system and surgeon's estimate for accurate

evaluation of acetabular cup orientation during total hip arthroplasty in supine position. *European Journal of Orthopaedic Surgery and Traumatology*, *30*(4), 707–712. https://doi.org/10.1007/s00590-020-02625-2

155. Hasegawa, M., Naito, Y., Tone, S., Wakabayashi, H., & Sudo, A. (2021). Accuracy of acetabular cup insertion in an anterolateral supine approach using an accelerometer-based portable navigation system. *Journal of Artificial Organs*, *24*(1), 82–89. https://doi.org/10.1007/s10047-020-01206-8
156. Lass, R., Kubista, B., Olischar, B., Frantal, S., Windhager, R., & Giurea, A. (2014). Total Hip Arthroplasty Using Imageless Computer-Assisted Hip Navigation. *The Journal of Arthroplasty*, *29*(4), 786–791. https://doi.org/10.1016/j.arth.2013.08.020
157. Sugano, N., Takao, M., Sakai, T., Nishii, T., & Miki, H. (2012). Does CT-based navigation improve the long-term survival in ceramic-on-ceramic THA? *Clinical Orthopaedics and Related Research*, *470*(11), 3054–3059. https://doi.org/10.1007/s11999-012-2378-4
158. Paprosky, W., & Muir, J. (2016). Intellijoint HIP: a 3D mini-optical navigation tool for improving intraoperative accuracy during total hip arthroplasty. *Medical Devices: Evidence and Research*, *Volume 9*, 401–408. https://doi.org/10.2147/MDER.S119161
159. Stiehl, J. B., Heck, D. A., Jaramaz, B., & Amiot, L.-P. (2007). Comparison of fluoroscopic and imageless registration in surgical navigation of the acetabular component. *Computer Aided Surgery*, *12*(2). https://doi.org/10.3109/10929080701292939
160. Kiefer, H., & Othman, A. (2007). Ultrasound vs pointer palpation based method in THA navigation: a comparative study. *Orthopedics*, *30*(10 Suppl), S153-6.
161. Hasart, O., Poepplau, B. M., Asbach, P., Perka, C., & Wassilew, G. I. (2009). Ultrasound-Based Navigation and 3D CT Compared in Acetabular Cup Position. *Orthopedics*, *32*(10/SUPPLEMENT), 6–10. https://doi.org/10.3928/01477447-20090915-50
162. Pearce, C. J., Sexton, S. A., Davies, D. C., & Khaleel, A. (2008). The transverse acetabular ligament may be used to align the acetabular cup in total hip arthroplasty. *Hip International*, *18*(1), 7–10. https://doi.org/10.5301/HIP.2008.5625
163. Archbold, H. A. P., Mockford, B., Molloy, D., McConway, J., Ogonda, L., & Beverland, D. (2006). The transverse acetabular ligament: an aid to orientation of the acetabular component during primary total hip replacement. *The Journal of Bone and Joint Surgery. British Volume*, *88-B*(7), 883–886. https://doi.org/10.1302/0301-620X.88B7.17577
164. Mihalko, W. M., Kammerzell, S., & Saleh, K. J. (2009). Acetabular Orientation with Different Pelvic Registration Landmarks. *Orthopedics*, *32*(10/SUPPLEMENT), 11–13. https://doi.org/10.3928/01477447-20090915-51
165. Hakki, S., Dordelly, L., & Oliveira, D. (2008). Comparative study of acetabular center axis vs anterior pelvic plane registration technique in navigated hip arthroplasty. *Orthopedics*, *31*(10 Suppl 1).
166. Wolf, A., DiGioia, A. M., Mor, A. B., & Jaramaz, B. (2005). Cup Alignment Error Model for Total Hip Arthroplasty. *Clinical Orthopaedics and Related Research*, *NA;*(437), 132–137. https://doi.org/10.1097/01.blo.0000164027.06880.3a
167. Takeda, Y., Fukunishi, S., Nishio, S., Fujihara, Y., & Yoshiya, S. (2017). Accuracy of Component Orientation and Leg Length Adjustment in Total Hip

Arthroplasty Using Image-free Navigation. *The Open Orthopaedics Journal*, *11*(1). https://doi.org/10.2174/1874325001711011432

168. Verdier, N., Billaud, A., Masquefa, T., Pallaro, J., Fabre, T., & Tournier, C. (2016). EOS-based cup navigation: Randomised controlled trial in 78 total hip arthroplasties. *Orthopaedics and Traumatology: Surgery and Research*, *102*(4), 417–421. https://doi.org/10.1016/j.otsr.2016.02.006
169. Gandhi, R., Marchie, A., Farrokhyar, F., & Mahomed, N. (2009). Computer navigation in total hip replacement: A meta-analysis. *International Orthopaedics*, *33*(3), 593–597. https://doi.org/10.1007/s00264-008-0539-6
170. Moskal, J. T., & Capps, S. G. (2011). Acetabular Component Positioning in Total Hip Arthroplasty: An Evidence-Based Analysis. *The Journal of Arthroplasty*, *26*(8), 1432–1437. https://doi.org/10.1016/j.arth.2010.11.011
171. Liu, Z., Gao, Y., & Cai, L. (2015). Imageless navigation versus traditional method in total hip arthroplasty: A meta-analysis. In *International Journal of Surgery* (Vol. 21, pp. 122–127). Elsevier Ltd. https://doi.org/10.1016/j.ijsu.2015.07.707
172. Beckmann, J., Stengel, D., Tingart, M., Götz, J., Grifka, J., & Lüring, C. (2009). Navigated cup implantation in hip arthroplasty. *Acta Orthopaedica*, *80*(5), 538–544. https://doi.org/10.3109/17453670903350073
173. Agarwal, S., Eckhard, L., Walter, W. L., Peng, A., Hatton, A., Donnelly, B., & de Steiger, R. (2021). The Use of Computer Navigation in Total Hip Arthroplasty Is Associated with a Reduced Rate of Revision for Dislocation: A Study of 6,912 Navigated THA Procedures from the Australian Orthopaedic Association National Joint Replacement Registry. *The Journal of Bone and Joint Surgery. American Volume*, *103*(20). https://doi.org/10.2106/JBJS.20.00950
174. Montgomery, B. K., Bala, A., Huddleston, J. I., Goodman, S. B., Maloney, W. J., & Amanatullah, D. F. (2019). Computer Navigation vs Conventional Total Hip Arthroplasty: A Medicare Database Analysis. *The Journal of Arthroplasty*, *34*(9), 1994-1998.e1. https://doi.org/10.1016/j.arth.2019.04.063
175. Gausden, E. B., Popper, J. E., Sculco, P. K., & Rush, B. (2020). Computerized navigation for total hip arthroplasty is associated with lower complications and ninety-day readmissions: a nationwide linked analysis. *International Orthopaedics*, *44*(3), 471–476. https://doi.org/10.1007/s00264-019-04475-y
176. Renkawitz, T., Weber, M., Springorum, H. R., Sendtner, E., Woerner, M., Ulm, K., Weber, T., & Grifka, J. (2015). Impingement-free range of movement, acetabular component cover and early clinical results comparing “femur-first” navigation and “conventional” minimally invasive total hip arthroplasty: A randomised controlled trial. *Bone and Joint Journal*, *97-B*(7). https://doi.org/10.1302/0301-620X.97B7.34729
177. Keshmiri, A., Schröter, C., Weber, M., Craiovan, B., Grifka, J., & Renkawitz, T. (2015). No difference in clinical outcome, bone density and polyethylene wear 5–7 years after standard navigated vs. conventional cementfree total hip arthroplasty. *Archives of Orthopaedic and Trauma Surgery*, *135*(5). https://doi.org/10.1007/s00402-015-2201-2
178. Parratte, S., Ollivier, M., Lunebourg, A., Flecher, X., & Argenson, J. N. A. (2016). No Benefit After THA Performed With Computer-assisted Cup Placement: 10-year Results of a Randomized Controlled Study. *Clinical Orthopaedics and Related Research*, *474*(10). https://doi.org/10.1007/s11999-016-4863-7

179. Illgen, R. L., Bukowski, B. R., Abiola, R., Anderson, P., Chughtai, M., Khlopas, A., & Mont, M. A. (2017). Robotic-Assisted Total Hip Arthroplasty: Outcomes at Minimum Two-Year Follow-Up. *Surgical Technology International*, *30*.
180. Nilsson, K. G., Theodoulou, A., Mercer, G., Quinn, S. J., & Krishnan, J. (2017). Mid-term migration of a cementless, porous acetabular cup: A 5 year Radiostereometric analysis. *Journal of Orthopaedics*, *14*(4). https://doi.org/10.1016/j.jor.2017.07.004
181. Grosser, D., Benveniste, S., Bramwell, D., & Krishnan, J. (2013). Early Migration of the R3 Uncemented Acetabular Component: A Prospective 2 Year Radiostereometric Analysis. *Journal of Surgery*, *1*(2).
182. Jacobsen, A., Seehaus, F., Hong, Y., Cao, H., Schuh, A., Forst, R., & Sesselmann, S. (2018). Model-based roentgen stereophotogrammetric analysis using elementary geometrical shape models: 10 years results of an uncemented acetabular cup component. *BMC Musculoskeletal Disorders*, *19*(1). https://doi.org/10.1186/s12891-018-2259-4

Appendix A: Ethics Approval

Western Research

Date: 22 November 2021

To: Dr. Brent Lanting

Project ID: 120151

Study Title: Retrospective Comparison of Hip Navigation Systems in Direct Anterior Approach to Total Hip Arthroplasty

Application Type: HSREB Initial Application

Review Type: Delegated

Full Board Reporting Date: 07/December/2021

Date Approval Issued: 22/Nov/2021

REB Approval Expiry Date: 22/Nov/2022

Dear Dr. Brent Lanting

The Western University Health Science Research Ethics Board (HSREB) has reviewed and approved the above mentioned study as described in the WREM application form, as of the HSREB Initial Approval Date noted above. This research study is to be conducted by the investigator noted above. **All other required institutional approvals and mandated training must also be obtained prior to the conduct of the study**.

Documents Approved:

Document Name	Document Type	Document Date	Document Version
120151 Data Collection Form 03-Nov-21	Other Data Collection Instruments	03/Nov/2021	1
120151 - Hip Navigation - 3-Nov-21	Protocol	03/Nov/2021	1

No deviations from, or changes to, the protocol or WREM application should be initiated without prior written approval of an appropriate amendment from Western HSREB , except when necessary to eliminate immediate hazard(s) to study participants or when the change(s) involves only administrative or logistical aspects of the trial.

REB members involved in the research project do not participate in the review, discussion or decision.

The Western University HSREB operates in compliance with, and is constituted in accordance with, the requirements of the Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans (TCPS 2); the International Conference on Harmonisation Good Clinical Practice Consolidated Guideline (ICH GCP); Part C, Division 5 of the Food and Drug Regulations; Part 4 of the Natural Health Products Regulations; Part 3 of the Medical Devices Regulations and the provisions of the Ontario Personal Health Information Protection Act (PHIPA 2004) and its applicable regulations. The HSREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000940.

Please do not hesitate to contact us if you have any questions. Sincerely,

Ms. Jhananiee Subendran, Ethics Coordinator on behalf of Dr. Philip Jones, HSREB Chair

Note: This correspondence includes an electronic signature (validation and approval via an online system that is compliant with all regulations).

Appendix B: Image Permissions

Decker, Monica <mdecker@aaos.org> Mon, Aug 15, 7:49 AM (13 days ago)

to me

Dear Dr. Loh,

Your request for permission was forwarded to my attention, thank you. You have permission to use the images referenced below from the *OrthoInfo* article in your thesis provided that you use the following credit line:

Reproduced with permission from OrthoInfo. © American Academy of Orthopaedic Surgeons. https://orthoinfo.org/

Sincerely,
Monica Decker

AAOS
American Academy of Orthopaedic Surgeons
American Association of Orthopaedic Surgeons

Monica Decker
Compliance Specialist
Office of General Counsel
9400 West Higgins Road, Rosemont, IL 60018
847.384.4047
mdecker@aaos.org

Appendix B: Image Permissions

Jeremy Loh 12 days ago

I am a Masters student at University of Western Ontario in London, Ontario Canada. My thesis is on comparing hip navigation accuracy in direct anterior approach hip replacements.

I was wondering if I could use the schematic diagram Fig 2. from your article https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2892068/.

Usage would be in the literature review of my thesis and full credit would be cited.

Sincerely,

Dr. Jeremy Loh MBBS, FRCS(C)

Saqeb B Mirza to you 12 days ago

Yes
That's ok

Curriculum Vitae

Dr. Jeremy Loh, MBBS FRCSC

BC License: 36872

Qualifications

MBBS (Hons.) 2014
ATLS 2016
LMCC 2017
FRCSC 2021
MSc Candidate 2021/2022

Education Honours & Awards

King's College University of London GKT Medical School 2008 – 2014
King's College University of London – MBBS 1 – Student Selected Components Merit (Top 15%)
King's College University of London – MBBS 2 – Academic Merit (Top 15%)
King's College University of London – MBBS 2 – Student Selected Components Merit (Top 15%)
King's College University of London – MBBS 4 – Academic Merit (Top 15%)
King's College University of London – MBBS 4 – Student Selected Components Merit (Top 15%)
JH Peel Prize – Outstanding performance in RSH MBBS 4 – 2013
King's College University of London – MBBS 5 – Student Selected Components Merit (Top 15%)
Bachelors of Medicine and Bachelor of Surgery – Pass with Distinction in Clinical Practice
Graduation July 31, 2014

Work Experience

South London and Maudsley (SLAM) NHS Foundation Trust – Lambeth Hospital, London
FY1 Doctor – Lambeth Triage (6/8/14 – 28/11/14)
Dr. Jonathan Beckett (Clinical Supervisor) & Dr. Martin Baggaley (SLAM medical director)
Guy's & St. Thomas NHS Foundation Trust, London
FY1 Doctor – Trauma & Orthopaedics (1/12/14 – 1/4/15)
Elective – Hip Firm (Mr. Bankes, Mr. Nunn, Mr. Shah, Mr. George, Mr. Khan)
Trauma – (Mr. Shah & Mr. George Orthopaedic Consultants)
FY1 Doctor – Old Age Medicine (1/4/15 – 31/7/15)
Dr. Rebekah Schiff (Clinical Lead Geriatrician Consultant)
Tunbridge Wells NHS Foundation Hospital (Pembury), Kent
FY2 SHO – Trauma & Orthopaedics (3/8/15 - 31/12/15)
FY2 SHO – Ear, Nose & Throat

Memorial University of Newfoundland July 1st 2016 – June 30th, 2021
Orthopaedic Surgery Residency Postgraduate Program

Western University August 1, 2021 – July 31, 2022
Adult Hip and Knee Reconstruction Fellowship
MSc Surgery Program
Lions Gate Hospital (North Vancouver, British Columbia)
Trauma Fellowship August 1st, 2021 – July 31st 2023

Medical Licensing
July 28, 2014 – June 30th 2016 – GMC (UK Full medical license) 7458263
July 1, 2016 – July 31th, 2021 – CPSNL (Newfoundland Educational License) R10043
Aug1st, 2021 – July 31st, 2022– CPSO Full license 119948
August 1st, 2022 – BC License Full - 36872

Medical Elective Experience
ENT surgery – Shastin Central Hospital, Ulaanbaatar, Mongolia – 2 weeks – August 2009
Pediatric Elective – BC Women's & Children's Hospital/ Thiessen, Paul & Associates – 3 week March 2014
Obstetrics & Gynecology Elective – Queen Mary Hospital & Tsan Yuk Hospital – 4 week July 2014
Emergency Medicine Elective – St. Francis Memorial Hospital – 4 week August 2014
Musculoskeletal Tumour & Adult Reconstructive Surgery – Royal National Orthopedic Hospital London – 4 week February 2016
Adult Orthopedics Community Rotation Elective – Richmond General Hospital, Vancouver – Jan/Feb 2019 - 6 weeks
Adult Orthopedics Community Rotation Elective – Burnaby Hospital , Vancouver – Feb/March 2019 - 6 weeks
Adult Hip and Knee Reconstruction Elective – University Hospital London Ontario – October 2019 – 4 weeks
Adult Sports Orthopaedics Elective – Mount Sinai Hospital / Women's College Toronto – November 2019 – 4 weeks
Adult Hip and Knee Reconstruction Elective – Vancouver General Hospital / UBC Hospital – December 2019 – 4 weeks

Leadership Experience
Foundation Programme Junior Doctor Representative – 2014/2015 Guy's & St. Thomas' Foundation Trust
Foundation Programme GSTT Community Attachment Committee member - 2014/2015
Memorial University Surgical Foundations Orthopaedic Representative – 2017 – present
PARNL Representative to MESC/PESC Educational Committee – 2018
Memorial University Orthopaedics Administrative Resident – 2019/2020 academic year

Audits & Research
BREAST OSNA audit – Darrent Valley Hospital - 2014
National CQUINN Psychiatric Triage Ward Audit – Lambeth Hospital – 2014
Elective Total Knee Replacement Analgesia Audit – Guy's Hospital -2015

Elective Orthopaedic TCI Pathway Service Improvement Project – Tunbridge Wells Hospital - 2016
Hip Fracture Bone Health Local Quality Improvement Audit– 2018

Loh, J., Cyr, K., & Martin, R. (2020). Ankle Fracture in Hereditary Sensory Neuropathy Type 1. *The Journal of Foot and Ankle Surgery*, Advance online publication. https://doi.org/10.1053/j.jfas.2020.09.015

Murphy JR, Loh J, Smith NC, Stone NC. Association of length of hospital stay with delay to surgical fixation of hip fracture. Can J Surg. 2022 Mar 15;65(2):E188-E192. doi: 10.1503/cjs.017520. PMID: 35292524; PMCID: PMC8929431.

COA Poster presentation 2021: Loh J., Murphy J., Stone C., Smith N. (2021) Time to Surgery and Mortality outcomes in rural and urban hip fracture patients

COA Poster presentation 2021: Murphy J., Loh J., Stone C., Smith N. (2021) Delay in surgical fixation of hip fractures is associated with increased hospital stay.

References
Available on request.