

Prediction of Iliopsoas Tendonitis after Hip Arthroplasty

By

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ABSTRACT

In 2007, total hip arthroplasty (THA) was labelled as the 'operation of the century' in The Lancet. With all its advancements in surgical techniques and approaches, technology utilisation, and implant development, this operation has restored mobility and quality of life (QoL) to millions of people who are suffering from debilitating deterioration of their hip joint. Despite this, many patients still suffer devastating postoperative complications that require revision, such as dislocation, infection, or loosening. However, significant research has been directed towards these complications, and less research has been directed towards other sources of postoperative dissatisfaction, such as soft tissue complications. These soft tissue complications may or may not require revision of the components, but they do significantly impact QoL and reduce postoperative function.

One of the main reported soft tissue complications after hip arthroplasty surgery is iliopsoas tendonitis, which has several causes, but is mainly attributed to impingement between an exposed acetabular cup and the iliopsoas muscle, causing irritation. Despite its relatively high incidence of between 4-30%, which varies by the type of hip arthroplasty surgery and the population of patients being studied, this complication is under-studied. Most research in this area has focused on identifying the incidence of iliopsoas tendonitis from Level-IV evidence retrospective database studies or assessing the success of various treatment regimens. Almost no research has been conducted to identify preoperative risk factors for iliopsoas tendonitis, let alone research towards the development of computational simulations for iliopsoas tendonitis. The development of a computational simulation for identifying iliopsoas tendonitis has significant potential. It could be used diagnostically by providing surgeons with enhanced clinical information about a patient who is suffering from postoperative groin pain and assist in their determination of an appropriate treatment pathway. Moreover, it could be used preventatively by integrating the simulation into a preoperative planning system to identify when patients may be at increased risk of iliopsoas tendonitis, allowing for patient-specific changes to the planned component positions and orientations to reduce this risk.

This dissertation therefore sought to address this gap in the literature by developing a computational simulation that can detect impingement between the iliopsoas and acetabular cup in patients who have undergone hip arthroplasty surgery, and then use this simulation to identify preoperative risk factors that exacerbate the risk of iliopsoas tendonitis. The ultimate ambitions for this tool were two-fold. First, to be used diagnostically by enabling postoperative assessment of patients who are experiencing groin pain. It was hoped that feedback from these postoperative assessments would facilitate improved treatment selection for patients with iliopsoas tendonitis by providing surgeons with more information about the nature of patient's groin pain. Second, it was

anticipated for this tool to be integrated into a preoperative planning protocol to guide and optimise the positioning of components to reduce the incidence of iliopsoas tendonitis.

The outcome of this thesis is a simulation that has been developed and tested in both THA and hip resurfacing arthroplasty patients. This testing involved correlating the primary output of the model – iliopsoas impingement – against clinical outcomes in case-controlled investigations of symptomatic and asymptomatic patients. These studies found the simulation to be more accurate in the identification of iliopsoas tendonitis, as measured by its sensitivity, specificity, and area under the curve in receiver operating characteristic curves, than the typical approach of measuring the anterior prominence of the acetabular cup on a CT scan. Following this, the simulation was applied to the preoperative setting where it was used to identify preoperative risk factors that may exacerbate the risk of iliopsoas tendonitis. This study found that posterior pelvic tilt of 6.0° and a delta between the native femoral head diameter and acetabular cup diameter of 5.7mm were significant predictors of iliopsoas tendonitis. Having completed these studies, integration of this tool into the 360Hip™ preoperative planning software has commenced, and will become a routine aspect of this system's optimised preoperative templating algorithm.

DECLARATION

I certify that this thesis:

1. does not incorporate without acknowledgment any material previously submitted for a degree or diploma in any university
2. and the research within will not be submitted for any other future degree or diploma without the permission of Flinders University; and
3. to the best of my knowledge and belief, does not contain any material previously published or written by another person except where due reference is made in the text.

Signed: MHM

Date: 02-April-2024

CONFLICTS OF INTEREST STATEMENT

This PhD dissertation was completed with the support of 360 Med Care, a for-profit company, where I was employed full-time for the majority of the time I was a PhD student. The support provided by 360 Med Care included, but was not limited to, use of their pre- and post-operative patient data and funding to present the research at national and international conferences.

360 Med Care intend to utilise the research generated from this dissertation to further enhance their preoperative planning system, which is a revenue-generating activity for the company.

All efforts have been made to manage these conflicts of interest in accordance with the ethical guidelines of Flinders University (including an Intellectual Property Agreement with the university), and to disclose these conflicts of interest in all published works derived from this dissertation. These disclosures can be viewed online in the published articles.

Signed: MHM

Date: 13-June-2024

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PUBLICATIONS

- ◇ *Pre- and postoperative physiotherapy using a digital application decreases length of stay without reducing patient outcomes following total knee arthroplasty.* Arthroplasty (2022). Max Hardwick-Morris, Simon Carlton, Joshua Twiggs, Brad Miles, David Liu.
- ◇ *Functional Femoral Anteversion: Axial Rotation of the Femur and its Implications for Stem Version Targets in Total Hip Arthroplasty.* Arthroplasty Today Vol. 18, 16-23 (2022). Max Hardwick-Morris, Joshua Twiggs, Kunaal Kacker, Brad Miles, Jitendra Balakumar.
- ◇ *Leg length discrepancy assessment in total hip arthroplasty: is a pelvic radiograph sufficient?* Bone & Joint Open (2023). Max Hardwick-Morris, Estelle Wigmore, Joshua Twiggs, Brad Miles, Christopher W. Jones, Piers J. Yates.
- ◇ *Iliopsoas tendonitis after total hip arthroplasty: an improved detection method with applications to preoperative planning.* Bone & Joint Open (2023). Max Hardwick-Morris, Joshua Twiggs, Brad Miles, Rami M. A. Al-Dirini, Mark Taylor, Jitendra Balakumar, William L. Walter.
- ◇ *Comparison of iliopsoas tendonitis after hip resurfacing arthroplasty and total hip arthroplasty: a case-controlled investigation using a validated simulation.* Journal of Orthopaedic Research (2024). Max Hardwick-Morris, Joshua Twiggs, Brad Miles, Rami M. A. Al-Dirini, Mark Taylor, Jitendra Balakumar, William L. Walter.
- ◇ *Determination of preoperative risk factors for iliopsoas tendonitis after total hip arthroplasty: a simulation study.* Journal of Orthopaedic Research (2024). Max Hardwick-Morris, Joshua Twiggs, Brad Miles, Rami M. A. Al-Dirini, Mark Taylor, Jitendra Balakumar, William L. Walter.

AWARDS

- ◇ Author Feature: Bone and Joint Open, June 2023;
<https://boneandjoint.org.uk/journal/BJO/author-features>
- ◇ Best Poster Presentation: *Does the iliopsoas act as an anterior stabiliser? A case series investigating a newly proposed source of iliopsoas tendonitis after total hip arthroplasty (POSTER).* Australian Orthopaedic Association and New Zealand Orthopaedic Association combined Annual Scientific Meeting 2022.
- ◇ Excellence Award: Arthroplasty (journal) for the publication *Pre- and postoperative physiotherapy using a digital application decreases length of stay without reducing patient outcomes following total knee arthroplasty;* <https://arthroplasty.biomedcentral.com/asia2022>

PRESENTATIONS

2023

Australian Orthopaedic Association Annual Scientific Meeting, November 2023

- ◇ *Clinical Implications of Range of Motion Differences Between Total Hip Arthroplasty and Hip Resurfacing Arthroplasty: A Preoperative Simulation Study.*
Joshua Twiggs; Max Hardwick-Morris; Brad Miles; William Walter; Kaushik Hazratwala; Tyson Doneley.
- ◇ *Prevalence of sagittal spinal malalignment in patients with iliopsoas tendonitis following total hip arthroplasty: a retrospective study.*
TBC
- ◇ *Anteversion vs. Medialisation: Comparing Strategies to Mitigate Iliopsoas Impingement in Total Hip Arthroplasty.*
Joshua Twiggs; Brad Miles; Max Hardwick-Morris; William Walter; Tyson Doneley; Kaushik Hazratwala.

International Society for Technology in Arthroplasty Annual Congress, September 2023

- ◇ *Anteversion vs. Medialisation: Comparing Strategies to Mitigate Iliopsoas Impingement in Total Hip Arthroplasty.*
Joshua Twiggs; Brad Miles; Max Hardwick-Morris; William Walter; Tyson Doneley; Kaushik Hazratwala.
- ◇ *Iliopsoas Tendonitis After Total Hip Arthroplasty: Development of an Instantaneous Risk Prediction Simulation.*
Joshua Twiggs; Max Hardwick-Morris; Brad Miles; Kaushik Hazratwala; Tyson Doneley; William Walter.
- ◇ *Clinical Implications of Range of Motion Differences Between Total Hip Arthroplasty and Hip Resurfacing Arthroplasty: A Preoperative Simulation Study.*
Joshua Twiggs; Max Hardwick-Morris; Brad Miles; William Walter; Kaushik Hazratwala; Tyson Doneley.

Computer Assisted Orthopaedic Surgery, June 2023

- ◇ *Is the mechanism of iliopsoas tendonitis the same in total hip arthroplasty as hip resurfacing arthroplasty? A case-controlled investigation using a validated simulation*
Max Hardwick-Morris; Rami Al-Dirini; Mark Taylor; William Walter; Joshua Twiggs; Brad Miles

- ◇ *Determination of preoperative risk factors for iliopsoas tendonitis after total hip arthroplasty*
Max Hardwick-Morris; Rami Al-Dirini; Mark Taylor; Jitendra Balakumar; William Walter; Joshua Twiggs; Brad Miles
- ◇ *Over 50% of patients at risk of impingement after THA surgery are not captured with neutral bony alignment*
Max Hardwick-Morris; Evan Jones; Warwick Bruce; William Walter; Joshua Twiggs; Brad Miles

2022

Orthopaedic Research Society Annual Meeting, February 2022

- ◇ *Internal Femoral Rotation & Anterior Pelvic Tilt in The Flexed Seated Position: Co-incidence And Functional Consequences*
Max Hardwick-Morris; Kunaal Kacker; Joshua Twiggs; Brad Miles
- ◇ *Leg Length Discrepancy Assessment in Total Hip Arthroplasty: Time to Get It Right (POSTER)*
Piers Yates; Christopher W. Jones; Max Hardwick-Morris; Estelle Liu; Joshua Twiggs; Brad Miles
- ◇ *Validation of a Novel Computational Iliopsoas Impingement Detection Model for Surgical Planning (POSTER)*
Bill Walter; Sam Khadra; Joshua Twiggs; Max Hardwick-Morris
- ◇ *Functional Femoral Anteversion: Axial Rotation of The Femur and its Implications for Stem Version Targets in Total Hip Arthroplasty (POSTER)*
Kunaal Kacker; Max Hardwick-Morris; Joshua Twiggs; Brad Miles

Computer Assisted Orthopaedic Surgery ASM, June 2022

- ◇ *Leg Length Discrepancy Assessment in Total Hip Arthroplasty: Time to Get It Right*
Joshua Twiggs; Christopher W. Jones; Piers Yates; Max Hardwick-Morris; Brad Miles
- ◇ *Functional Femoral Anteversion: Axial Rotation of the Femur and Its Implications for Stem Version Targets in Total Hip Arthroplasty*
Max Hardwick-Morris; Joshua Twiggs; Kunaal Kacker; Jitendra Balakumar; Brad Miles
- ◇ *Validation of a Novel Computational Iliopsoas Impingement Detection Model for Surgical Planning*
Max Hardwick-Morris; Joshua Twiggs; Mark Taylor; Rami Al-Dirini; Brad Miles; Jitendra Balakumar; Bill Walter
- ◇ *Internal Femoral Rotation & Anterior Pelvic Tilt in the Flexed Seated Position: Co-Incidence and Functional Consequences (POSTER) – Awarded Best Poster Presentation*
Estelle Liu; Max Hardwick-Morris; Joshua Twiggs; Kunaal Kacker; Jitendra Balakumar; Brad Miles

EFORT Congress Lisbon, June 2022

- ◇ Rotation of the Femur in Total Hip Arthroplasty: Functional Femoral Version an Underestimated Problem?
Christoph Hartog; Kunaal Kacker; Max Hardwick-Morris; Joshua Twiggs; Jitendra Balakumar

International Society for Technology in Arthroplasty Annual Congress, September 2022

- ◇ *Leg Length Discrepancy Assessment in Total Hip Arthroplasty: Time to Get It Right*
Max Hardwick-Morris; Joshua Twiggs; Brad Miles; Christopher Jones; Piers Yates
- ◇ *Validation of a Novel Computational Iliopsoas Impingement Detection Simulation for Surgical Planning*
Brad Miles; Max Hardwick-Morris; Joshua Twiggs; Yuan Chai; Jitendra Balakumar; Mark Taylor; Rami Al-Dirini; William Walter
- ◇ *Novel Methodology for Measuring the Medial Proximal Tibial Angle in Total Knee Arthroplasties*
William Walter; Ishaan Jagota; Matthew Lim; Joshua Twiggs; Brad Miles; Max Hardwick-Morris
- ◇ *Population Level Validation of a Novel Joint Distraction Radiology Protocol in Total Knee Arthroplasty Planning*
Joshua Twiggs; Ishaan Jagota; David Liu; Brad Miles; Max Hardwick-Morris
- ◇ *Over 50% of Patients at Risk of Impingement after THA Surgery are Not Captured with Neutral Bony Alignment*
Brad Miles; Joshua Twiggs; Max Hardwick-Morris; Estelle Liu
- ◇ *Functional Femoral Anteversion: Axial Rotation of the Femur and Its Implications for Stem Version Targets in Total Hip Arthroplasty*
Max Hardwick-Morris; Joshua Twiggs; Kunaal Kacker; Brad Miles; Jitendra Balakumar
- ◇ *Validation of a Novel Computational Iliopsoas Impingement Detection Simulation for Surgical Planning (POSTER)*
Brad Miles; Max Hardwick-Morris; Joshua Twiggs; Yuan Chai; Jitendra Balakumar; Mark Taylor; Rami Al-Dirini; William Walter

Australian Orthopaedic Association / New Zealand Orthopaedic Association Combined Annual Scientific Meeting, October 2022

- ◇ *Application of the Simple Hip-Spine Classification to an Australian sample to determine local patient-specific cup orientation requirements*
Max Hardwick-Morris; Evan Jones; Warwick Bruce; William Walter; Joshua Twiggs; Brad Miles

- ◇ *Are the causes of iliopsoas-related groin pain in total hip arthroplasty and hip resurfacing arthroplasty similar? A case-controlled investigation using a validated simulation*
Max Hardwick-Morris; Rami Al-Dirini; Mark Taylor; William Walter; Joshua Twiggs; Brad Miles
- ◇ *Determination of preoperative risk factors for iliopsoas tendonitis after total hip arthroplasty*
Max Hardwick-Morris; Rami Al-Dirini; Mark Taylor; Jitendra Balakumar; William Walter; Joshua Twiggs; Brad Miles
- ◇ *Over 50% of patients at risk of impingement after THA surgery are not captured with neutral bony alignment*
Max Hardwick-Morris; Evan Jones; Warwick Bruce; William Walter; Joshua Twiggs; Brad Miles
- ◇ *Does the iliopsoas act as an anterior stabiliser? A case series investigating a newly proposed source of iliopsoas tendonitis after total hip arthroplasty (POSTER) – Awarded Best Poster Presentation*
Max Hardwick-Morris; Kunaal Kacker; Lachlan Milne; Jitendra Balakumar

2021

Australian Orthopaedic Association COE, April 2021

- ◇ *Pre-operative Planning to Avoid Impingement in THR?*
Warwick Bruce, Max Hardwick Morris, Joshua Twiggs
- ◇ *AI, Data Ownership & the Blockchain*
Brett Fritsch, Max Hardwick Morris, Joshua Twiggs

Asia Pacific Arthroplasty Society, August 2021

- ◇ *Psoas Irritation with THA – Diagnosis and Management*
Bill Walter, Max Hardwick-Morris

Australian Orthopaedic Association ASM, November 2021

- ◇ *Validation of a novel computational iliopsoas impingement detection model for surgical planning*
Bill Walter, Sam Khadra, Yuan Chai, Wout Veltman, Max Hardwick-Morris
- ◇ *Functional Femoral Anteversion: Axial Rotation of the Femur and its Implications for Stem Version Targets in THA*
Kunaal Kacker, Max Hardwick-Morris, Joshua Twiggs, Jitendra Balakumar
- ◇ *Internal femoral rotation and anterior pelvic tilt from supine-to-flexed seated and the risk of dislocation*
Kaushik Hazratwala, Max Hardwick-Morris, Evan Jones, Jitendra Balakumar, Warwick Bruce

- ◇ *Remote pre- and rehabilitation as an in-patient rehabilitation alternative in patients undergoing total knee replacement*

David Liu, Simon Carlton, Ishaan Jagota, Max Hardwick-Morris, Joshua Twiggs, Brad Miles

CHAPTER 1: LITERATURE REVIEW

Anatomy of the Hip

The hip joint is a ball-and-socket joint formed by the acetabulum of the pelvis and head of the proximal femur.¹ The ball-and-socket structure of the hip joint permits tri-planar rotation in the coronal, sagittal, and axial planes. Specifically, these motions are flexion and extension in the sagittal plane, abduction and adduction in the coronal plane, and internal and external rotation in the axial plane.² The hip joint has a high active range of motion with approximately 120 degrees of flexion, 30 degrees of extension, 45 degrees of abduction, 35 degrees of adduction, and 45 degrees of internal or external rotation.^{3–8} During dynamic movements, the forces from the upper body may be several times greater than body's weight when static. Therefore, some of the primary functions of the hip include supporting the upper body and efficiently distributing forces to the lower limbs.⁹

Bony Anatomy

The acetabulum is a confluence of three pelvic bones: the ischium, ilium, and pubis. The proximal aspect of the femur is comprised of the femoral head, femoral neck, and femoral shaft, corresponding to the epiphysis, metaphysis, and diaphysis, respectively. The femoral head is a conchoid shape, which provides stability to the joint by reducing the likelihood of subluxation and contributes to more optimal distribution of stress.^{10,11} Significant variability in the shape of these two bony structures exists between individuals, and these have significant impacts on the optimal orientation and selection of implants in hip arthroplasty. An illustration of the bony anatomy of the pelvis and femur, and a selection of key parameters and landmarks that are relevant to hip arthroplasty surgery, can be found in Figure 1.

On the femoral side, bone morphology can be described by the neck-shaft angle and femoral anteversion. The neck-shaft angle is typically $125^{\circ} \pm 5^{\circ}$ and has a significant impact on the femoral offset, which is the distance from the femoral head centre to the femoral axis.^{12–15} The femoral offset determines the mechanical advantage of the abductor muscles, which attach to the superior aspect of the ilium and insert at the greater trochanter (GT). Femoral offset has been linked the femoral neck-shaft angle;^{12–14} lower neck-shaft angles, termed coxa vara, typically result in higher femoral offsets, and subsequently, have greater moment arms acting on the abductor muscles. Conversely, higher neck-shaft angles, termed coxa valga, typically exhibit lower femoral offsets, and result in the abductors experiencing reduced moment arms. Hip joints with coxa valga femurs, lower femoral offset, and lower abductor moment arms therefore have larger hip contact forces and abductor muscle forces.^{15,16}

Femoral anteversion is the angle between the femoral neck axis and the posterior condylar line (PCL) and is, on average, about 15 degrees.² However, significant variability of up to 80 degrees exists.^{17–23} Extreme anteversion (or retroversion, also termed negative anteversion) requires compensatory rotation at the hip to maintain joint congruency. Extreme anteversion may also impact the efficiency of the soft tissue structures attaching to the femur. Specifically, excessive anteversion posteriorises the femur, changing the moment arm in the gluteus muscles and creating laxity.² Additionally, compensatory mechanisms have been proposed whereby dramatic intraoperative changes to the native femoral anteversion with implanted components that anteriorises or posteriorises the femur leads to subsequent internal or external rotation of the femur to maintain joint tensioning.²⁴ The bony anatomy of the hip can be found in Figure 1.

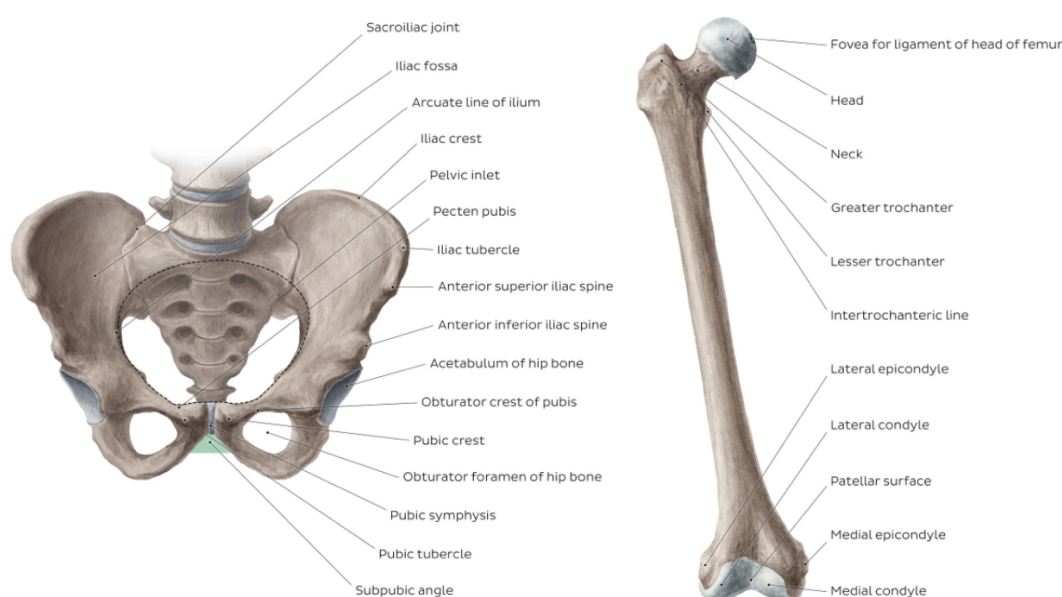


Figure 1 The bony anatomy of the hip from (a) coronal view and (b) lateral view. Images have been licensed with permission from Kenhub GmbH.

Capsular & Ligamentous Anatomy

The pelvis and femur are connected by the capsular ligaments (Figure 2); a confluence of cylindrical, dense fibres that insert superiorly at the acetabular periosteum and inferiorly at the intertrochanteric line. Additionally, the acetabulum, which is shaped like an incomplete hemisphere structure with a notch on the inferior side, is bridged by the transverse acetabular ligament (TAL). This ligament assists in maintaining the integrity of articulation and stability of the hip joint.² These ligaments consist predominantly of type-1 collagen (~85%) and combinations of type III, V, VI, XI, and XIV (~15%), and contribute to distinct roles of motion and stability at the hip joint.^{25,26} The iliofemoral ligament is the primary restraint for external rotation in flexion and anterior translation. It also restrains internal rotation in neutral and extension. The ischiofemoral ligament restrains

internal rotation at neutral and during combined flexion with adduction. The pubofemoral ligament restrains external rotation, particularly during extension. The zona orbicularis is the locking ring around the femur and neck, and is essential for distraction stability. The labrum contributes less rotational restraint compared to the iliofemoral ligament and intact capsule. Finally, the ligamentum teres, once thought to be a vestigial feature with no role or contribution to stabilisation is now understood to act as a secondary restraint for external rotation during flexion with abduction and adduction.^{27–29}

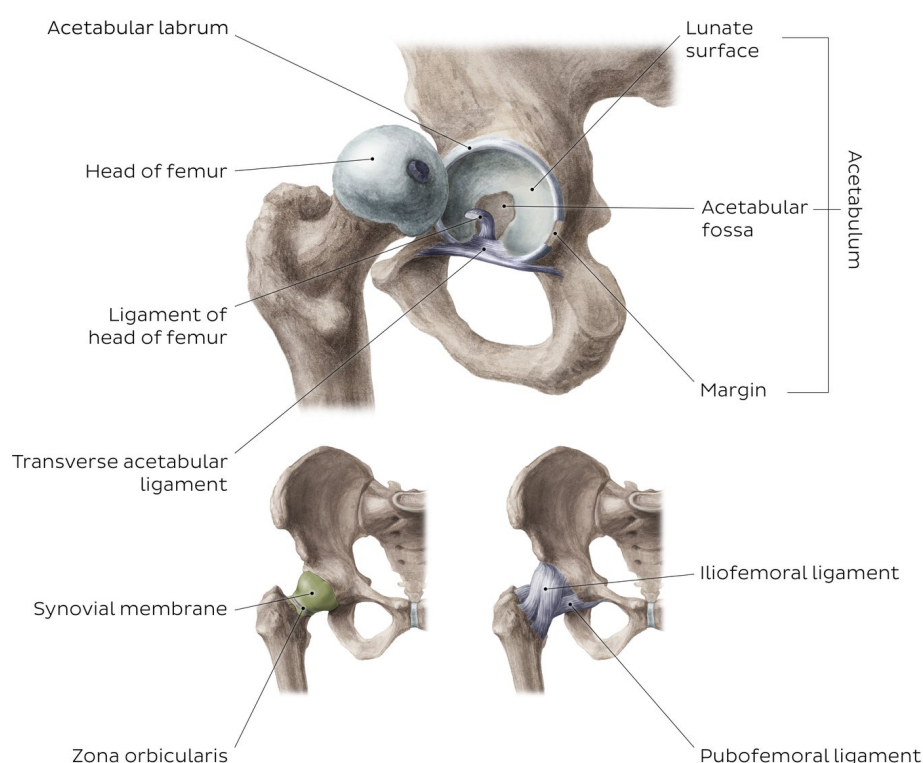


Figure 2 Anatomy of the capsular ligaments around the hip joint can be found in the lower right aspect, including the iliofemoral ligament and the pubofemoral ligament. Image has been licensed with permission from Kenhub GmbH.

Muscular Anatomy

The hip joint contains many muscles that can be grouped into anterior (flexor), posterior (extensor), lateral (abductor), and medial (adductor) muscles.³⁰ The primary flexor muscles of the hip are the iliopsoas complex, which is formed by the psoas major and the iliacus, and the rectus femoris. The iliopsoas attaches to the lesser trochanter, the iliac crest of the pelvis, and the lumbar spine, and transmits forces across both the hip joint and lumbar spine. The rectus femoris attaches at both the hip and knee joints, similarly transmitting forces across both these. It is worth noting that the

iliopsoas has several other functions, including abduction and internal rotation of the thigh, flexion and lateral flexion of the lumbosacral spine, and axial twisting of the lumbosacral spine. Iliopsoas disorders can occur due to the muscle being overworked, or from weakness and subsequent issues in handle the stresses imposed on it. For example, iliopsoas contracture will manifest as pain around the femoral head, lumbosacral spine, and groin with longer term effects that include limited active flexion of the hip, pelvic obliquity, and functional shortening of the leg with concomitant spinal issues, such as hyperlordosis, or scoliosis.³¹ The hip flexor muscles, including iliopsoas major, iliacus, rectus femoris, sartorius, and pectineus can be found in Figure 3.

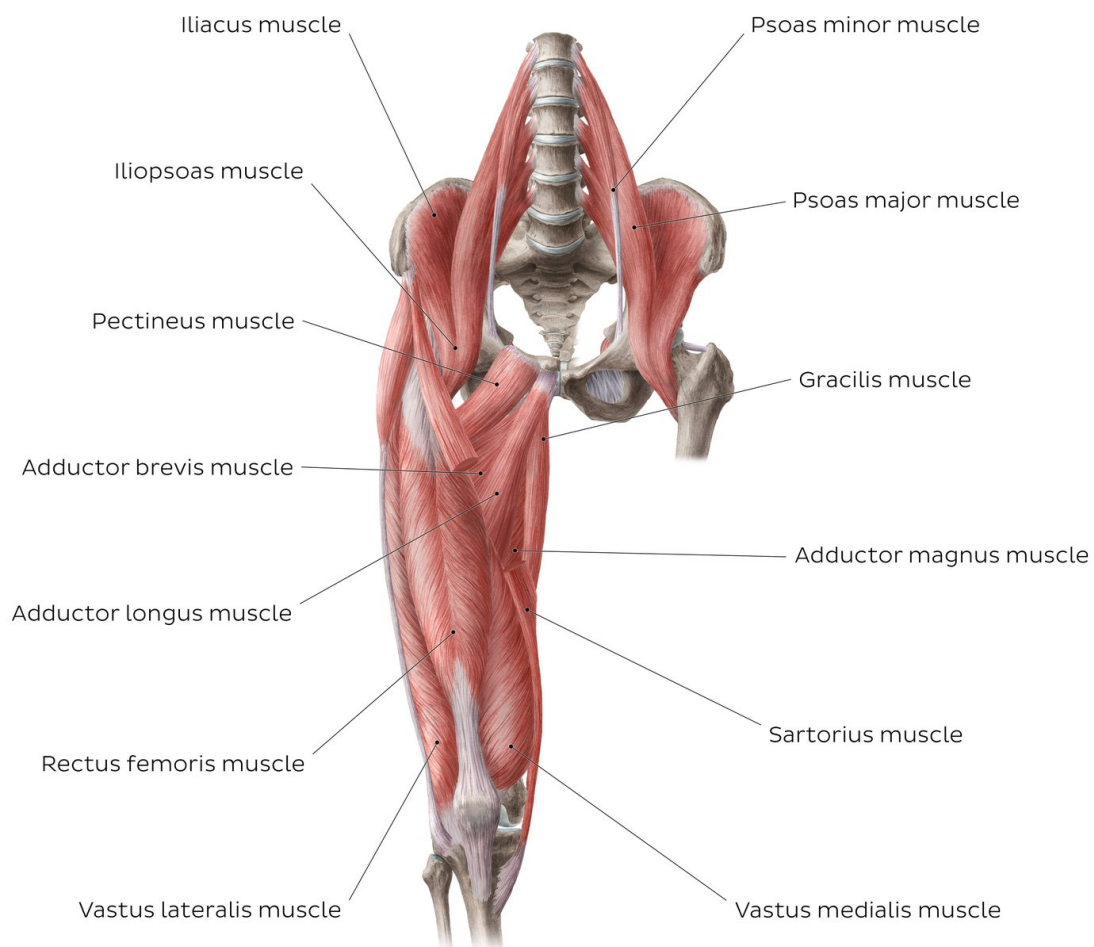


Figure 3 Muscles of the hip and thigh. The hip flexor muscle are noted, including the iliopsoas major, iliacus, rectus femoris, pectineus, and sartorius. Image has been licensed with permission from Kenhub GmbH.

The hip extensor muscles include the hamstrings and the gluteus maximus (Figure 4). The primary hip adductor muscles include the gracilis, adductor longus, adductor brevis, and adductor magnus. The hip abductor muscles include the gluteus medius, gluteus minimus, and tensor fascia latae.³²

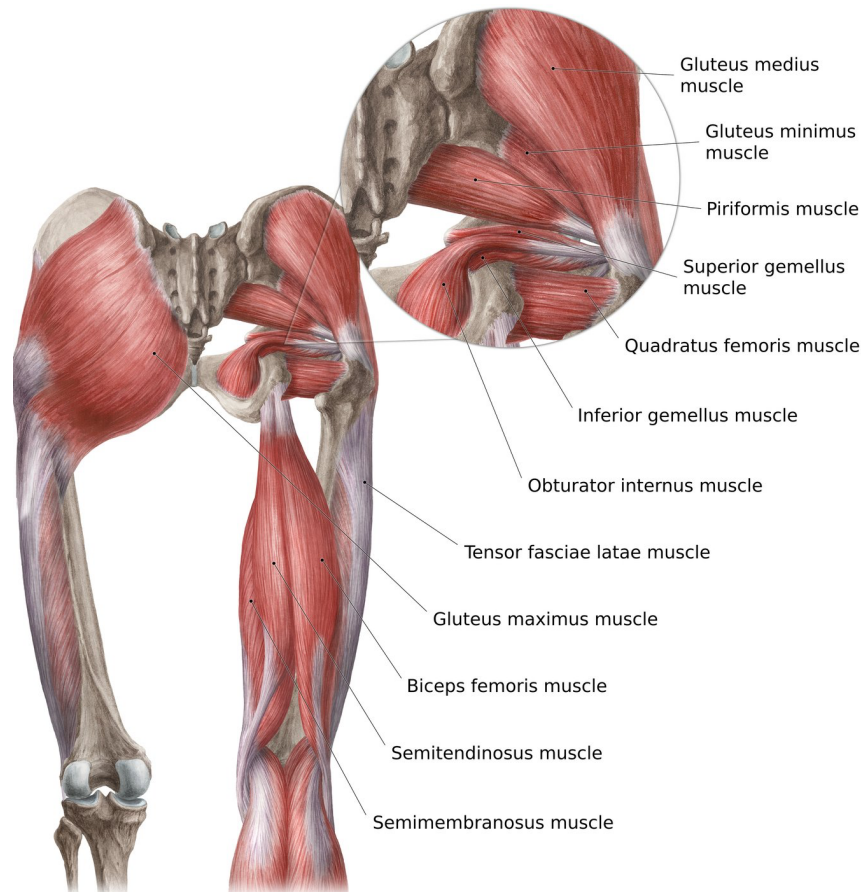


Figure 4 Muscles of the hip and thigh. The hip extensor muscles are noted, including around the hip joint, including the hamstrings (biceps femoris) and gluteus maximus. Image has been licensed with permission from Kenhub GmbH.

Biomechanics of the Hip

Understanding the biomechanics of the hip is critical in preoperative planning for hip arthroplasty surgery and implant development. Hip joint biomechanics are typically assessed as static free body diagrams in either a single-leg stance, representing the swing phase of the gait cycle, or a two-leg stance.^{33–35} In a two-leg stance, the weight of the body is transmitted equally through both legs, with the centre of gravity directed down the midline of the body.^{33–35} These biomechanical representations of the hip joint are acknowledged to be oversimplifications that only assess the forces acting in the coronal plane.³³ However, these free body diagrams allow for interpretable illustrations of the dramatic effect that small changes to the centre of rotation and femoral offset can have on the forces acting across the hip joint.

In a single-leg stance, the centre of gravity shifts away from the stance leg and towards the swing leg, which is represented in Figure 5.³³ In this diagram, W is the gravitational force, and is equal to the weight of the body minus the weight of the contralateral lower limb. W exerts a moment around the femoral head, which is counterbalanced by the abductor muscles, which are represented by A .

The moment arm of A around the femoral head is shorter than the moment arm of W , and is therefore a multiple of W . The magnitude of this force depends upon the offset of the femur. For example, a short femoral neck (low offset) and wide pelvis will produce higher hip forces (*ceteris paribus*).^{33,34} The reality of this is that women typically undergo relatively higher hip forces due to their wider pelvises and lower femoral offsets.³⁶ The resultant force of the femoral head exerted on the acetabulum, the joint reaction force, is represented by F .^{33,34}

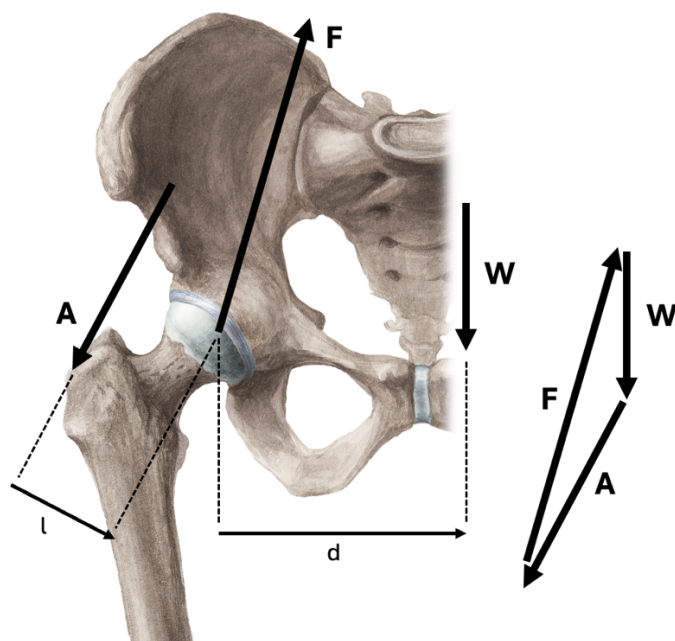


Figure 5 A simple free body diagram of the forces acting on the hip joint during single leg stance. Gravitational force W , abductor muscle force A , hip joint reaction force F , and force of gravity moment arm d . Image has been licensed with permission from Kenhub GmbH and vector arrows have been added.

While static analyses of forces acting on the hip joint are simple and useful, understanding the effects of motion and varying loads is more relevant to hip arthroplasty, and adds several degrees of complexity. Specifically, calculating the forces acting on the hip during dynamic activities, such as walking and running, requires extensive kinetic and kinematic data of the lower limbs. Research into this area has been undertaken in studies by Bergmann et al.³⁷ and Novacheck³⁸, who showed that, during slow walking, forces up to 3 times the body weight is loaded through the hip joint after heel strike. This force then increases to four times the body weight just before the foot leaves the ground. In running, forces of up to 7 to 8 times body weight may be loaded through the hip joint at heel strike, with a slight increase at the point of toe-off. It is worth noting that a limitation of these analyses is that they consider only linear motion (walking or running in a straight line), and do not consider activities that involve more complex lateral movements, such as pivoting movements. In several studies, Bergmann et al.^{37,39,40} obtained *in vivo* measurements with pressure transducers inside THA implants and confirmed earlier *ex vivo* calculations that the forces acting through the hip joint during dynamic movements can be up to 8 times body weight.

Total Hip Arthroplasty

Termed the 'operation of the century', total hip arthroplasty (THA) is an established and well accepted procedure for treating patients with end-stage osteoarthritis of the hip or other degenerative bone pathologies.^{41–43} However, the relatively low revision rates which this declaration reflects do not provide a holistic understanding of patient outcomes and between 7% and 23% of patients experience postoperative pain or dissatisfaction.^{44–46}

The operation in its current form was invented in the 1960s by John Charnley, who made three major contributions to the operation. First, the idea of low friction torque arthroplasty that emphasised the use of small diameter femoral heads to create the largest difference between the native femoral head diameter and the prosthetic femoral head diameter. Second, the use of acrylic bone cement to fix the implants to the bone. Third, the introduction of high-density polyethylene (PE) as a bearing material. Prior to this, various iterations of prosthetic designs and materials were betrayed due to poor designs, inferior materials, or mechanical failure.^{41,47,48}

THA surgery was initially reserved to the elderly or infirm population, as potential benefits did not outweigh the risks and outcomes associated with the surgery for younger patients. However, due to improvements in implant design, bearing surfaces, planning technologies and techniques, and surgical execution technologies, such as computer assisted surgical units and robots, younger patients are being indicated for THA.⁴¹

Primary THA surgery may be performed through several different surgical approaches, depending upon surgeon experience and preference, and includes acetabular reconstruction with an acetabular cup in addition to resection of the femoral head and replacement with a stemmed femoral prosthesis.⁴⁹ These prostheses may be uncemented or cemented, and can be seen in Figure 6 below. Preparation of the femur involves broaching or rasping the femoral canal to insert the femoral stem. Preparation of the acetabulum involves reaming to create a smooth and hemispherical surface, followed by insertion of a hemispherical or ellipsoid cup. Generally, surgeons will aim to approximately restore pre-arthritic or pre-pathological native anatomy in terms of joint centre of rotation (COR) and femoral offset to restore function and mobility to the hip.^{50,51}

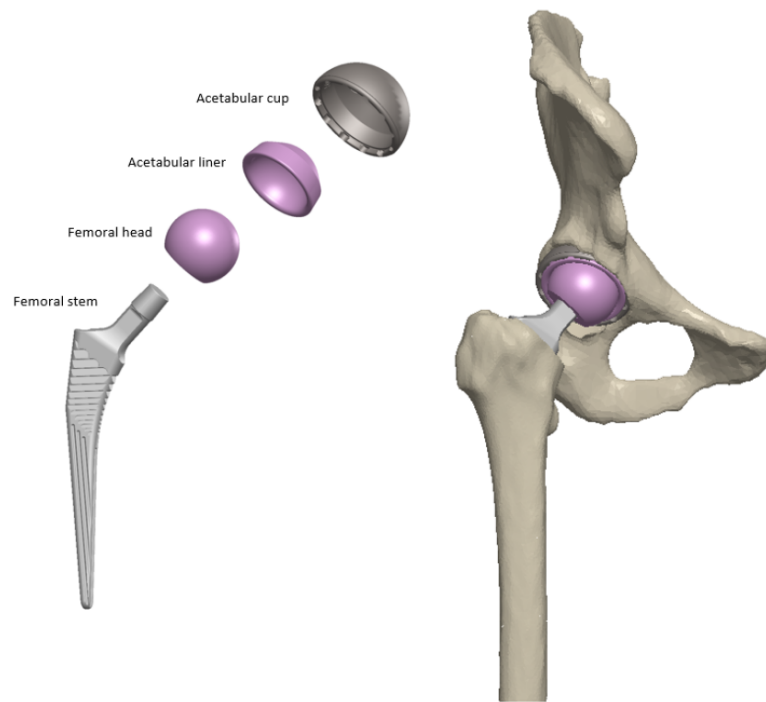


Figure 6 The implant components in THA: Femoral stem, femoral head, acetabular liner, and acetabular cup. The bearing surfaces are the femoral head and acetabular liner. The fixed, bone-contacting components are the femoral stem and acetabular cup.

Epidemiology & Trends

The number of THAs per year have been steadily increasing in recent decades. For example, Australia has seen a 123.5% increase since 2003, and 2020 was the only year on record that saw a reduction in the number of hip replacements. However, this was a result of the COVID pandemic that resulted in the cancellation of elective surgery.⁴⁹ In Australia, primary THA is more common in females than males, as seen in Figure 7 below.⁴⁹

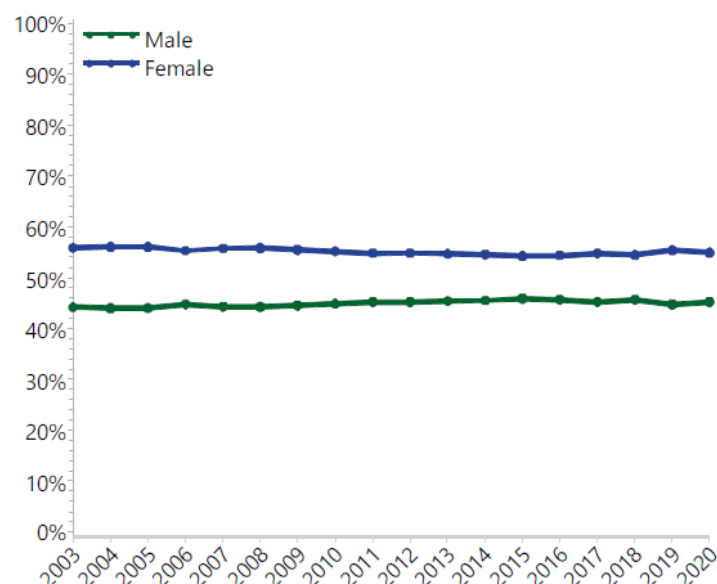


Figure 7 Primary total conventional hip replacement by gender (Figure HT1, AOANJRR 2021).

The mean age for THA surgery is 67.8 years old and all age groups have remained relatively constant in their proportion of the total number of operations, as seen in Figure 8 below.⁴⁹

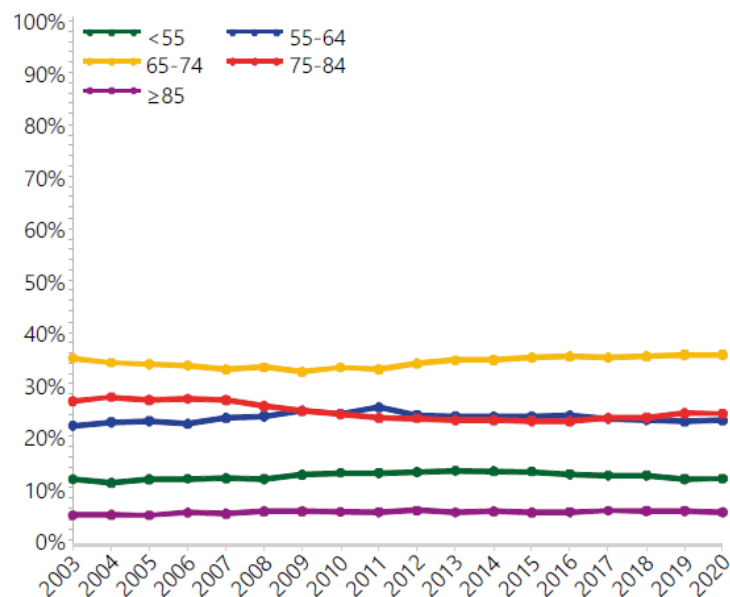


Figure 8 Primary total conventional hip replacement by age (Figure HT2, AOANJRR 2021).

One distinct trend has been the increase in the use of cementless fixation, which has increased from 51.3% in 2003 to 60.8% in 2020. Hybrid fixation, which utilises cemented (typically for the femoral component) and uncemented fixation (typically for the acetabular component) has also seen an increase from 34.8% to 36.8% in the same period. Cemented fixation has declined from 13.9% to 2.4%.⁴⁹

The most common principle indications for THA surgery are osteoarthritis (87.6%), fractured neck of femur (5.6%), osteonecrosis (3.2%), developmental dysplasia (1.3%), rheumatoid arthritis (0.8%), and tumour (0.6%). Osteoarthritis has the lowest rate of revision amongst these principle diagnoses, whereas tumours and fractured neck of femurs typically result in the highest rate of revision.⁵²

Complications

In Australia, the most common reasons for revision of a primary THA are infection (23.3%), fracture (22.0%), dislocation and instability (21.7%), loosening (20.8%), and many other causes, including pain, leg length discrepancy, and implant breakage. Dislocation and instability are combined as they reflect a similar cause of revision surgery.⁵² Interestingly, the relative frequency of the reasons for revision vary over time. In the first 11 years, dislocation and infection are the most common reasons for revision whereas, after 11 years, loosening is the predominant reason for revision. Additionally, the cause of loosening varies over time. In the first years after initial implantation,

loosening reflects an inability to acquire fixation with the bone. In later years, loosening reflects a loss of fixation following osteolysis that leads to bone resorption.⁴⁹ The cumulative revision rate for THA in Australia can be seen in Figure 9⁴⁹ below.

Hip Class	N Revised	N Total	1 Yr	3 Yrs	5 Yrs	10 Yrs	15 Yrs	20 Yrs
Total Conventional	12028	368834	1.6 (1.5, 1.6)	2.3 (2.3, 2.4)	2.9 (2.8, 3.0)	4.4 (4.3, 4.5)	6.5 (6.3, 6.7)	9.0 (8.3, 9.8)
TOTAL	12028	368834						

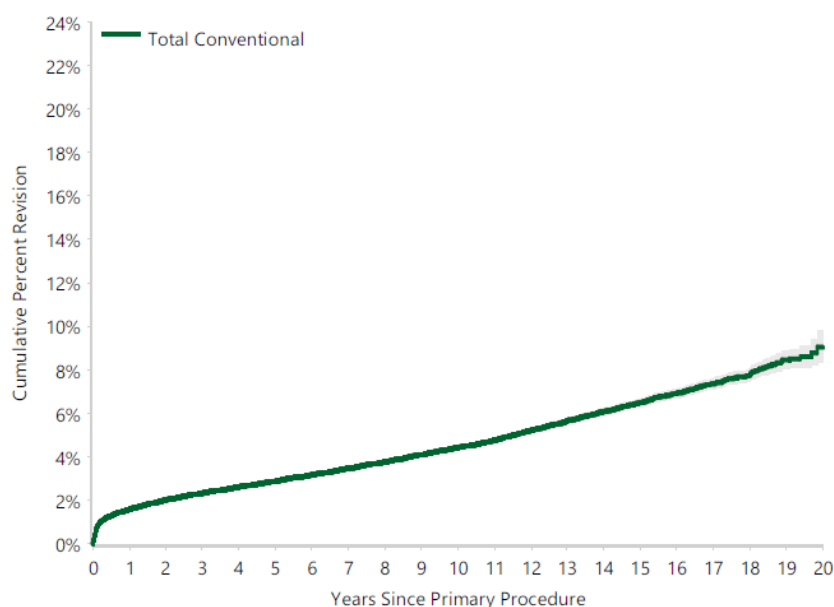


Figure 9 Cumulative percent revision of primary total conventional hip replacement (primary diagnosis OA) (Table HT14 and Figure HT5, AOANJRR 2021).

Regarding implant fixation type, there are no long-term differences in the overall rate of revision for cemented fixation compared to hybrid fixation, whereby hybrid fixation refers to a cemented femoral component and cementless acetabular component. However, differences in rates of revision do arise when examining the postoperative period in segments. For example, cementless fixation has a higher rate of revision than hybrid fixation in the immediate three years after operation (2.5% vs. 2.1%),⁵² followed by no difference after this three-year mark. There are also differences in the outcomes of fixation types with respect to the age of the patient. For example, cementless fixation has higher rates of revision in elderly populations when compared to hybrid and cemented fixations.⁴⁹ For example, the 1-year revision rates in patients old than 75 years old are 2.2% for cementless, 1.4% for hybrid, and 1.2% for cemented.⁵² It is worth noting that despite statistical differences existing between these rates of revision between implant fixation types, the absolute difference in these rates of revision is generally minor.

Dislocation

Dislocation and instability are well-known complications following THA surgery; they are leading causes of revision THA in several national joint registries.^{53,54} It is difficult to establish with certainty whether dislocation rates reduced over time, but a number of innovations in implant design, implant sizing, preoperative planning with patient-specific component alignments, and intraoperative navigation technologies, have been linked to a gradual reduction of this complication.^{55–57}

One of the initial changes to surgical technique that led to a dramatic reduction in rates of dislocation was the advent of posterior capsule repair.^{58–61} This was first proposed by Pellicci et al. after noting fluid-filled dead space after incising the fascia lata was a common finding in revision THAs. The authors hypothesised this was due to a lack of posterior soft-tissue repair.⁶¹ Several studies later validated this hypothesis that the posterior stabilising structures should be preserved and repaired as well as possible by altering their surgical technique and noting significant reductions in the incidence of instability and dislocations from 4-8% to 0-1%.^{58–60}

With significant improvements in stability arising from posterior capsule repair, research into femoro-acetabular kinematics, femoral head jump distance, and impingement free range of motion (ROM) was also underway.⁵⁵ In a multicentre study that investigated the role of femoral head diameter and its relationship to dislocation, the authors noted that dislocated hips were 2.3 times more likely to become recurrent if a small diameter femoral head was used.⁶² Similar findings of larger diameter femoral heads reducing the incidence of dislocation have been found in prospective randomized,⁶³ retrospective,⁶³ cadaveric,⁶⁴ and registry⁶⁵ studies. On the acetabular side, Cobb et al. noted that a 10° elevated-rim liner had a dislocation rate of 2.2%, compared to 3.9% with a neutral liner.⁶⁶ Similarly, several studies have noted reductions in rates of dislocation with the use of dual mobility articulations.^{67,68}

The Hip-Spine Relationship: The Evolution of Functional Thinking to Improve Rates of Instability

Lewinnek et al.⁶⁹ were some of the first authors to investigate the relationship between dislocation and cup orientation when they proposed a 'safe zone' (LSZ) of 40° inclination and 15° anteversion ($\pm 10^\circ$) in 1978. However, there were several limitations to this paper, specifically:

- ◇ The study utilised a relatively small sample of ~300 patients with 9 dislocations;
- ◇ Due to inaccuracies associated with radiographic imaging in the 1970s, a generic adjustment was applied to all measurements of anteversion to correct for distortion;
- ◇ A rudimentary and, likely, inaccurate technique for pelvic tilt neutralisation was used whereby a tripod with a bubble was used to position the pelvis level to the film;
- ◇ Only 113 radiographic images were measured and the distribution of results from these patients were extrapolated to the remainder of the cohort;

- ◇ Of the nine dislocations, six had prior surgery. Though, no description of the previous surgeries was given; and
- ◇ The senior surgeon completed 190 of the hip replacements, had only one dislocation, did not have any greater percentage of acetabular cups within the safe zone, used different implants to the other surgeons, and was the only surgeon to regularly reattach the external rotators;

Despite these limitations, the LSZ became the gold standard for cup placement and comparison in published literature, positioning itself as 17th in an analysis of the most widely cited papers in orthopaedics⁷⁰ (regardless of the fact that the vast majority of studies that cite the LSZ do so incorrectly⁷¹). However, subsequent, larger analyses of acetabular cup positioning in dislocating and non-dislocating THA patients found that the LSZ was not a good predictor of stability and the risk of dislocation.^{72,73} In fact, one of these studies found the majority of dislocations occurred within the LSZ.⁷² These authors concluded stability is multifactorial and cup positioning may need to be considered at an individual-level with more advanced analyses needed in a subgroup of patients.⁷²

One of the main drivers of this inability to determine a generic acetabular cup orientation that would be appropriate for everyone is the large variability of pelvic tilt in functional positions, which is when dislocation is most likely to occur, and the large variability of pelvic rotation that can occur between positions,^{74,75} with some individuals rotating as little as 5° between functional positions and others as much as 70°. ⁷⁴ Knowing that 1° of change in pelvic tilt corresponds to a change in anteversion of 0.7°, ⁷⁶ patients at the tail ends of the pelvic rotation distribution undergo a change in anteversion of up to 50°, which dramatically alters their risk of edge loading, prosthetic impingement with subsequent dislocation, and wear.^{57,77–89}

With this understanding of the degree of inter-patient variability in pelvic kinematics, and the influence of spinal alignment on the orientation of the pelvis, significant research efforts have since been devoted towards understanding the hip-spine relationship,^{8,56,90–105} with efforts made towards bridging the gap between hip and spine surgeons.⁹¹ A table of the key spinopelvic measurements and parameters (both static and dynamic) can be found in Table 1.^{93,98,106,107}

Table 1 Relevant measurements for spinopelvic mobility in the total hip arthroplasty literature with their associated descriptions, landmarks, and an interpretation of the values.

Measurement	Description	Landmarks	Notes/Interpretation
<i>Pelvic tilt (PT)</i>	Sagittal position of the pelvis relative to the vertical (functional) plane.	An angle between a vertical line and the anterior pelvic plane (APP) where the APP is defined by the pubic symphysis and the left and right anterior superior iliac spine (ASIS) points.	ΔPT between positions reflects the magnitude of pelvic rotation between positions.
<i>Spinopelvic Tilt (SPT)</i>	Sagittal position of the pelvis relative to the sacral end plate (S1).	An angle formed by a line from the midpoint of S1 to the centre of the bicoxofemoral axis and a vertical line.	ΔSPT between positions is the same as ΔPT .
<i>Sacral Slope (SS)</i>	Partly determines the position of the lumbar spine.	An angle formed by a line parallel to S1 and the horizontal.	ΔSS between positions is the same as ΔPT and ΔSPT .
<i>Pelvic Incidence (PI)</i>	A position independent parameter of an individual's pelvic morphology that reflects the anatomic position of the hip relative to the sacrum.	An angle formed by a line from the midpoint of S1 to the centre of the bicoxofemoral axis and a line perpendicular to the centre of S1.	The greater the PI, the more anterior the hip joint relative to the acetabulum. A greater PI will result in greater ΔPFA from stand to seated. Low: $< 42^\circ$ Normal: $42^\circ < PI < 64^\circ$ High: $> 64^\circ$
<i>Pelvic-femoral angle (PFA)</i>	Position of the femur relative to the sacral end plate.	An angle formed by a line from the centre of S1 to the centre of the femoral head and down 10cm of the ventral cortex of the femur.	PFA reflects the combined pelvic and femoral position. ΔPFA is the hip flexion between positions. The smaller the angle in standing, the more pronounced the fixed flexion contracture of the hip. A conventional value for ΔPFA is between 55° - 70° ; elevated value are typically due to pelvic stiffness. ¹⁰⁷
<i>Lumbar lordosis (LL)</i>	Degree of lumbar lordosis of the spine.	Cobb angle between the end plate of S1 and the sacral end plate.	Lumbar flexion (ΔLL) has been used to identify spinal stiffness. Lumbar flexion when LL reduces, and extension was LL increases. ΔLL of less than 20° has been suggested to be a risk factor for dislocation. ^{98,108}

<i>Anteinclination (AI)</i>	Sagittal orientation of acetabular cup and a measure of operative plane anteversion ^{107,109} .	An angle formed by the long axis of the cup and a horizontal reference projection.	AI is a component of a proposed 'functional safe zone' using the formula: $AI + PFA = CSI^{107}$; where CSI = combined sagittal index.
<i>Pelvic Mobility (PM)</i>	Degree of pelvic movement through the sagittal plane from standing to seated positions. Posterior tilt of the pelvis accommodates a flexing femur.	The change in pelvic tilt (ΔPT) or sacral slope (ΔSS) between standing and seated. ΔPT and ΔSS are equivalent; held constant by the formula $PI = SS + PT$.	A stiff spinopelvic juncture (also referred to as a 'stiff pelvis') is defined as PM of less than 10°^{110} . This is a key risk factor for dislocation after THA ¹¹¹ .
<i>Spinopelvic balance (PI-LL mismatch)</i>	A measure of an individual's sagittal balance. In a healthy spine, the degree of pelvic incidence is counterbalanced by greater curvature (lordosis) of the spine.	Difference between PI and LL.	Normal range is -10° to 10° . $PI - LL > 10^\circ$ considered to be flatback deformity ^{93,110} (kyphosis). Hyper-lordosis is considered $< -10^\circ$.
<i>Combined Sagittal Index (CSI)</i>	A static value measured in functional positions that has been shown to be a predictor of THA instability.	The sum of AI and PFA; typically calculated in standing and seated positions.	Thresholds of CSI in standing have been found to be significant predictors of THA instability. $CSI_{standing} < 216^\circ$ is a predictor of posterior instability. $CSI_{standing} > 244^\circ$ is predictor of anterior instability.
<i>Hip-User Index (HUI)</i>	The percentage contribution of sagittal femoral and pelvic movement (ΔPFA), relative to the overall sagittal movement ($\Delta PFA + \Delta LL$).	$\frac{\Delta PFA}{\Delta LL + \Delta PFA} * 100$	Larger values suggest a greater change in the pelvic femoral angle, which has been suggested as a risk factor for dislocation ⁹⁸ .

Soft Tissue Complications

Another common category of complications after THA surgery, which are a source of persistent pain and discomfort that can lead to revision surgery or other corrective procedures, are soft tissue complications. Diagnoses of soft tissue complications are typically made once other, potentially more urgent, sources of pain have been ruled out, including infection or loosening. Capogna et al.¹¹² outlined three of the most common tendon disorders after THA with their corresponding evaluation and management.

Greater Trochanteric Pain Syndrome

Greater Trochanteric Pain Syndrome (GTPS) is used to describe a lateral hip pain after THA surgery. The pain has typically been attributed to trochanteric bursitis.¹¹³ However, a study of patients after THA surgery who presented with symptomatic lateral hip pain thought to be trochanteric bursitis showed no signs of inflammation of the bursa when compared to a control cohort of patients.¹¹⁴ This led the authors to conclude that there was no inflammatory component, and that other diagnoses should be considered. Further confirmation of this can be found in a study by Kingzett-Taylor et al.,¹¹⁵ which reviewed MRIs of patients with lateral hip pain and determined that tendinopathy was present in many of the patients with pain, and a frequent source of pain in GTPS. Therefore, GTPS is a complicated and multifactorial pathological process that is likely related to excessive friction between the iliotibial band (ITB) and the greater trochanter (GT), which may be a result of increased offset or leg length added intraoperatively.¹¹⁶

History and Physical Examination

GTPS typically presents after a pain-free period after surgery as the underlying friction accumulates and develops into pain. The pain is distinct from the groin pain that was related to the osteoarthritis, and the pain is most intense when the affected side is weight-bearing (standing or walking). Due to this pain and associated weakened abductors, Trendelenburg gait is common amongst patients suffering from GTPS.¹¹²

Imaging and Diagnostic Studies

Imaging is not always required to diagnose a patient with GTPS; however, it will usually be undertaken to rule out other diagnoses, such as a femoral fracture or component loosening. An MRI will provide useful information regarding the condition of the soft tissue structures around the hip joint and permit the clinician to determine the presence of tendinopathy and fluid within the trochanteric bursa.^{112,113}

One of the most useful diagnostic tools for all soft tissue complications after THA surgery is the injection of a mixture of corticosteroid and local anaesthetic into the affected soft tissue structure. When this procedure is performed accurately into the source of pain, the injection will perform as a diagnostic tool, and as a source of pain relief. The pain relief from the injection will, in most cases,

be temporary. However, further injections can be performed in the future to delay more invasive procedures or achieve more permanent pain relief.¹¹²

Management

Management of GTPS can be targeted via both operative or non-operative means, and will vary between clinician recommendations, patients and their tolerance for different procedures, and the severity of pain. Non-operative management usually commences with the prescription of non-steroidal anti-inflammatory drugs (NSAIDs) combined with physical therapy. As mentioned above, a corticosteroid-anaesthetic injection may also be utilised to provide pain relief and assist in diagnosis of GTPS. Patients may require multiple injections to achieve more lasting pain relief; however, many patients will experience complete symptom resolutions from injections.^{113,116} It should be noted that failure of symptom resolution or pain relief from injections has been associated with inaccurate injection technique.¹¹⁷

Operative treatment is available for patients that do not respond adequately to non-operative management. This treatment option involves a partial release of the ITB and can be performed via open or arthroscopic means.¹¹³ Several techniques have been described,^{113,118,119} however, the ultimate goal of this procedure is to reduce friction of the ITB over the GT.

Iliopsoas Tendonitis

Another frequent source of postoperative pain from THA surgery is iliopsoas tendonitis. This disorder manifests as groin pain that is exacerbated by active flexion movements and will be discussed at length in the following section.

Iliopsoas Tendonitis

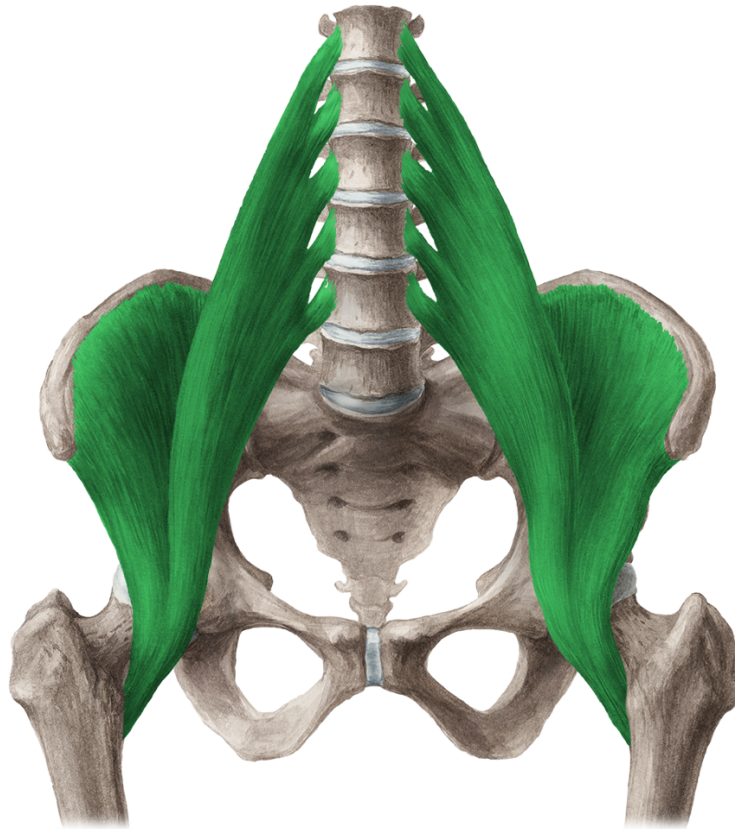


Figure 10 Anatomy of the iliopsoas, which consists of two muscles: the iliacus and the psoas major. Image has been licensed with permission from Kenhub GmbH.

Anatomy of Iliopsoas

The iliopsoas (Figure 10) serves as the major hip flexor, with a lesser role in external rotation.¹²⁰ It consists of two smaller muscles: the psoas major, which originates at the lumbar spine, and the iliacus, which originates at the upper two-thirds of the fossa iliaca. These two muscles are joined by the iliopsoas tendon, which inserts at the lesser trochanter (LT).^{31,120} Two anatomic variations of the iliopsoas tendon have been proposed (Figure 11).^{120,121} One variation, seen below in the image on the left, has a distinct separation of the iliopsoas muscle from the iliopsoas tendon with the crossing fibres of the iliacus discontinuing at the level of the femoral neck. The other variation, seen in Figure 11 on the right, has iliacus fibres continue further down the femoral neck with no discernible separation of the iliacus muscle and the iliopsoas tendon.

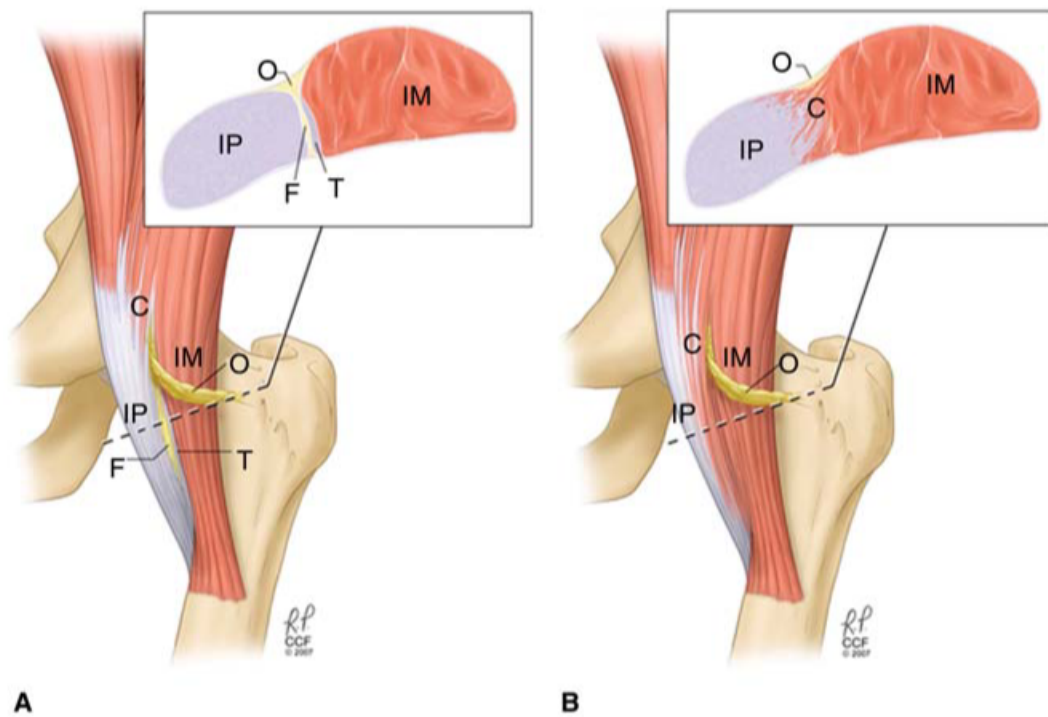


Figure 11 Two anatomic variations of the iliopsoas tendon have been proposed. One with a distinctly separate iliopsoas tendon from the iliacus muscle and one with cross-over between the two soft tissue structures. Reprinted with permission from Springer Nature.

The bursa ileus pectineal (iliopsoas bursa), which lies between the iliofemoral and pubofemoral ligaments, separates the iliopsoas complex from the hip capsule, and can be seen in Figure 12.¹²² The iliopsoas tendon is extra-articular. However, after THA surgery using the anterior approach, which resects the anterior capsule, the iliopsoas tendon may become intra-articular and intimately associated with the implants.¹²⁰

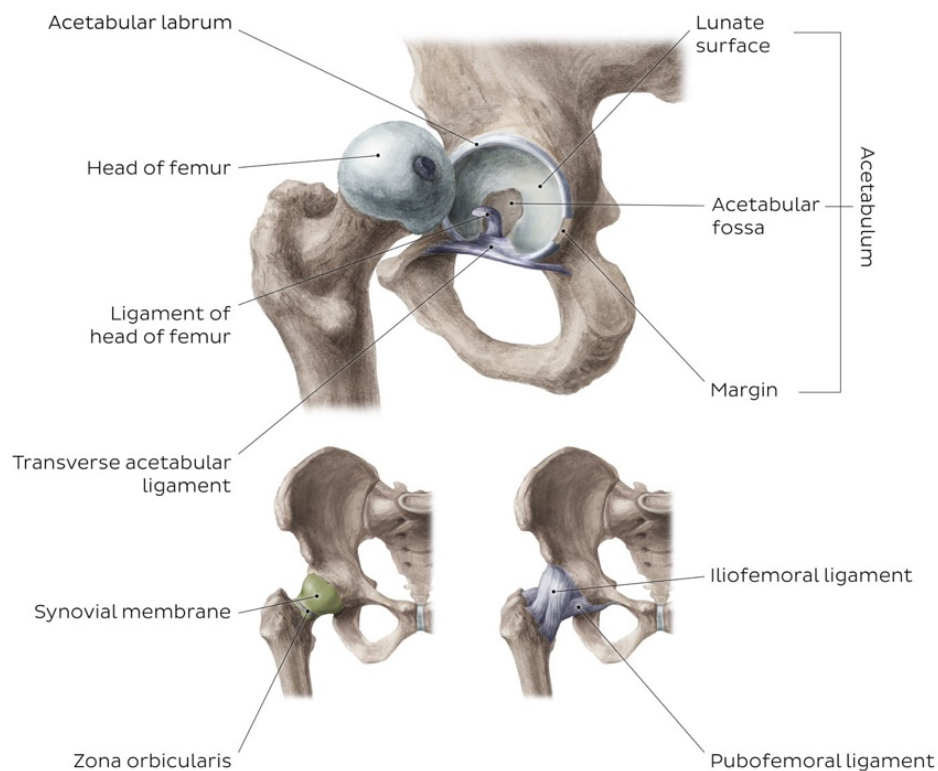


Figure 12 Anatomy of the ligaments that attach to the pelvis and proximal femur. The bursa ileus pectineal sits atop the iliofemoral and pubofemoral ligaments. Image has been licensed with permission from Kenhub GmbH.

Psoas Valley

The iliopsoas passes over the pelvis at the psoas valley, which is a small depression of the anterior acetabular margin, and can be seen in Figure 13.¹²³ The shape of this psoas valley has clinical implications for THA as the geometric mismatch between it and the acetabular cup, which can lead to a partially exposed prosthesis, increases the likelihood of irritation of the iliopsoas^{123,124} from chronic friction between the iliopsoas tendon and rim of the acetabular cup.^{112,125–127} Kuroda et al. performed a systematic review of the literature to investigate the variability in the psoas valley across the population and provide a unified definition of its shape. In this study, they considered five key descriptions of the psoas valley: depth, width, shape, location, and index of widening and determined that the most frequent shape for the psoas valley is curved, while the straight configuration has a low incidence.

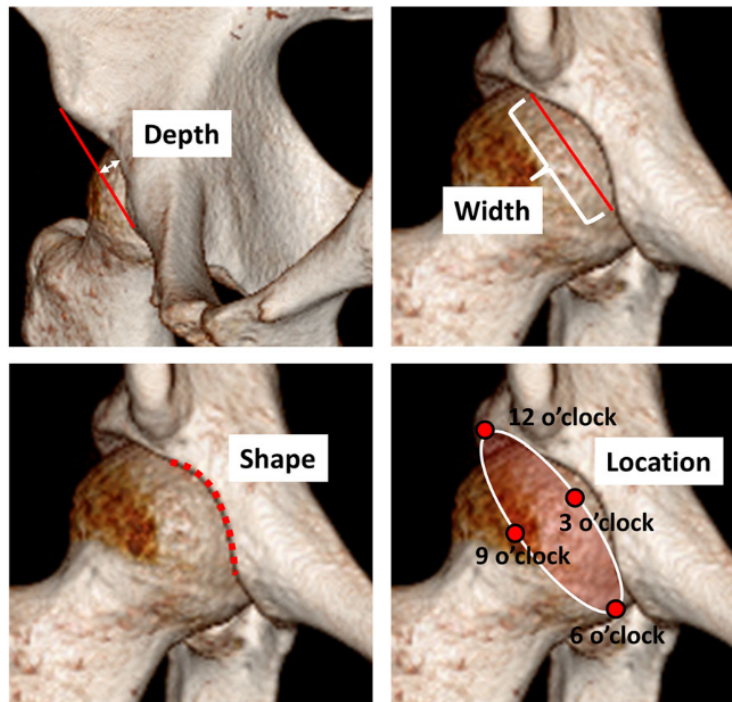


Figure 13 Dimensions of the psoas valley using recreation of the bony anatomy from a computed tomography scan. Amongst the papers surveyed in this study, depth was typically defined by authors as the straight line distance of the notch from a line joining the anterior inferior iliac spine and the iliopubic eminence; width was either defined in angular terms or a direct measurement of the distance between the two bony peaks; shape was described in qualitative terms, such as curved, angular, irregular, and straight; and location was described as a clockwise distribution with the acetabular notch as the baseline landmark to reference 6:00 from. Courtesy of Kuroda et al., 2020, BMC Musculoskeletal Disorders. This work is licensed under a Creative Commons Attribution License (CC BY 4.0).

Additionally, the psoas valley was found to be deeper in males and located at approximately 3 o'clock on the acetabulum.¹²³ Greater curvature and depth of the psoas valley are prone to prosthetic overlap of the acetabular cup, leaving part of it exposed, and would increase the risk of iliopsoas impingement. Vandenbussche et al.¹²⁴ reported a similar distribution of the shape of the psoas valley. In this study, the authors recreated the bony anatomy of 50 men and 50 women using CT scans and measured coordinates placed on the acetabular rim to determine the acetabular diameter, anteversion, acetabular inclination, and plot the profile of the acetabular rim. They concluded that the psoas valley was a curved shape in 79% of people, irregular in 10%, angular in 11%, and straight in 0%. Additionally, the authors suggested the use side-specific implants that replicate the native curved anatomy of the psoas valley to reduce the opportunity for iliopsoas impingement.

Incidence of Iliopsoas Tendonitis

The incidence of iliopsoas tendonitis after hip replacement surgery is highly variable in the literature.^{125,126,128–134} Some studies have reported it to be as high as 29% of patients after THA,¹³² whereas other studies have reported its incidence to be as low as 0.4%.¹³⁰ The incidence of iliopsoas tendonitis after HRA is more consistent and reported to be between 18-32%.^{132,133} A

summary of these studies investigating the incidence of iliopsoas tendonitis can be found in Table 2.

The wide variation in incidence can be partly explained by the heterogeneity of reporting in regards to duration of follow-up, varying descriptions of the site and severity of pain, and its treatment¹³⁵. Additionally, several of the most frequently cited studies into the incidence of iliopsoas tendonitis^{125,126,130} were limited to small samples of patients,^{125,126,130} were retrospective,^{125,126,130} and are now two decades old.^{125,126}

In one prospective study investigating the incidence of pain after THA, Nam et al.¹³² found an incidence of 29% of THA patients and 32% of HRA patients experience groin pain after THA. In another prospective study, Lavigne et al.¹³³ reported groin pain in 30.5% of HRA patients and 18.3% of THA patients. However, both studies were focused on younger patients who are more likely to be active and engage in activities that lead to groin discomfort. Moreover, the study by Nam et al.¹³² was an opt-in, survey-based study with a response rate of 59.7%, which introduces possible selection and participation biases.

Differences in incidence of iliopsoas tendonitis between surgical approaches have also been studied. In the first study of iliopsoas tendonitis after the direct anterior approach (DAA), Buller et al.¹³¹ conducted a retrospective analysis of 600 patients (655 hips) to investigate the incidence, history, and risk factors for iliopsoas tendonitis after DAA THA. This study found an incidence of 5.7%, higher than previous studies,^{125,126,130} and preoperative risk factors for increased incidence of iliopsoas tendonitis included female gender, an acetabular component to native femoral head diameter ratio above 1.1, and any measurable overhang of the acetabular component.¹³¹ In fact, women were nearly three times more likely to be diagnosed with iliopsoas tendonitis. Women also had larger differences between the native femoral head diameter and implanted acetabular cup diameter in both the symptomatic and asymptomatic cohorts. Similar results of a larger delta between acetabular cup diameter and femoral head diameter in patients with iliopsoas tendonitis have been observed in another study.¹³⁶ The authors therefore posited that the higher incidence of iliopsoas tendonitis in females resulted from a tendency to oversize the acetabular component to accommodate a larger prosthetic femoral head. The authors also posited that a higher prevalence of hip dysplasia, with its associated shallow acetabulum that may leave the acetabular cup unavoidably exposed, may explain some of the difference in incidence of iliopsoas tendonitis. However, other authors have noted no difference in iliopsoas tendonitis in patients with hip dysplasia.¹²⁸

In consideration of why the incidence of iliopsoas tendonitis may vary between surgical approach, the authors discussed the unique anatomical features of the DAA, which includes incision of anterior capsule. This incision may increase the risk of iliopsoas irritation by disrupting the protective layer of soft tissue separating the prosthetic cup and iliopsoas, intimately linking the

two.^{131,137} Additionally, DAA surgeons may also target a decreased cup anteversion orientation to protect from anterior instability. This decreased anteversion will lead to a greater chance of anterior exposure of the acetabular cup, resulting in concomitant iliopsoas impingement and irritation.

Due to various limitations of the studies that have investigated the incidence of iliopsoas tendonitis, it may true that an accurate and current incidence of iliopsoas tendonitis is unknown, particularly given the changes in surgical approach (an increase in utilisation of the DAA) and implant geometries in the past two decades.^{131,138–140} In fact, some recent implant geometries have been designed with the key goal in mind of reducing the incidence of iliopsoas tendonitis, including the H1 hip resurfacing component¹⁴¹ and anatomic prosthetic femoral head designs.¹⁴²

Table 2 Reported incidence of groin pain after THA and HRA. NR = not reported, DAA = direct anterior approach

Authors	No. of hips	Mean follow-up in months (range)	Incidence	Notes
THR				
Ala Eddine et al. ¹²⁵	206	7.3 (1-48)	4.4%	Iliopsoas tendonitis
Bricteux et al. ¹²⁶	280	NR (0-60)	4.3%	Iliopsoas tendonitis
Bartelt et al. ¹²⁹	217	14 (12-24)	7%	Conventional
Bartelt et al. ¹²⁹	65	14 (12-24)	15%	Metal-on-metal
Buller et al. ¹³¹	559	55.8 (24-126)	5.7%	Iliopsoas tendonitis, DAA only
Lavigne et al. ¹³³	85	N/A (3-24)	18.3% (3 months) 15.3% (12 months) 12.9% (24 months)	Metal-on-metal, 28mm head
Lavigne et al. ¹³³	89	N/A (3-24)	30.0% (3 months) 13.5% (12 months) 16.9% (24 months)	Metal-on-metal, large-head
Nam et al. ¹³²	196	34.8 (12-NR)	29%	Young patients (<60 years old)
O'Sullivan et al. ¹³⁰	3501	20 (2-96)	0.4%	Iliopsoas tendonitis requiring surgical release
HRA				
Bartelt et al. ¹²⁹	46	14 (12-24)	18%	HRA
Bin Nasser et al. ¹³⁴	116	26 (12-61)	18%	HRA
Lavigne et al. ¹³³	105	N/A (3-24)	30.5% (3 months) 15.2% (12 months) 14.9% (24 months)	HRA
Nam et al. ¹³²	224	34.8 (12-NR)	32%	HRA, young patients (<60 years old)

Diagnosis and Treatment of Iliopsoas Tendonitis

History and Physical Examination

Patients with iliopsoas tendonitis typically present with unrelenting groin pain that is exacerbated by activities of daily living (ADLs), such as climbing stairs or getting out of a car.^{112,137} The onset of symptoms is typically between 1 and 96 months.^{130,143} However, clinicians are wary of diagnosing this disorder too early due to the possibility of residual pain from the operation itself.

For physical examination, the surgeon may perform an active hip flexion test with the patient.^{112,144} This test involves positioning the patient in supine with the affected hip slightly flexed, abducted and externally rotated. A positive result indicating iliopsoas-related groin pain is determined by the following: the patient should not experience any pain between zero degrees of flexion (rest) and ten degrees of passive flexion, but experience pain with active flexion using a straight leg raise.

Imaging and Diagnostic Studies

If a patient presents with persistent groin pain after THA surgery, several possible sources of groin pain, such as infection, aseptic loosening, occult periprosthetic fracture, should be ruled out through a combination of inflammatory biomarker tests and imaging studies.¹²⁰ Infection can be ruled out with erythrocyte sedimentation rate (ESR) and C-reactive protein (CRP) inflammation biomarker tests. The normal values for ESR are 0-15 mm/h for men and 0-20mm/h for women and <1mg/dL for CRP.¹⁴⁵ Aseptic loosening and occult periprosthetic fracture can be ruled out with a combination of imaging studies, such as an anteroposterior (AP) pelvic x-ray and a 3-phase bone scan.^{112,145} The AP x-ray should be inspected for acetabular positioning, specifically, the lateralisation of the acetabular cup's centre of rotation (COR) and whether the acetabular anteversion is low or negative (retroverted), as this increases the likelihood of acetabular cup exposure.^{131,146} A cross-table lateral x-ray of the painful hip allows the clinician to determine whether there is any acetabular cup overhang that may be causing irritation of the iliopsoas.¹¹² This may also be assessed with a CT scan, which enables measurement of the acetabular anteversion and the acetabular cup prominence.¹²⁰

Two studies have reported acetabular cup prominence of between 2-12mm in patients with iliopsoas tendonitis.^{143,147} An example of a prominent cup can be found in Figure 14. It is worth noting that the CT scan in this figure has a clear delineation between implant and bone. However, in CT scans that have used lower radiation levels or have not utilised metal artefact reduction algorithms, the metal implant can produce significant flare and obscure the bony boundary. This may make it more difficult to ensure accurate measurement of the cup prominence. In addition to studies reporting cup prominence using other methods, such as cross-table radiographs, this flare may partly explain the reason for large differences in reported prominence values between studies.

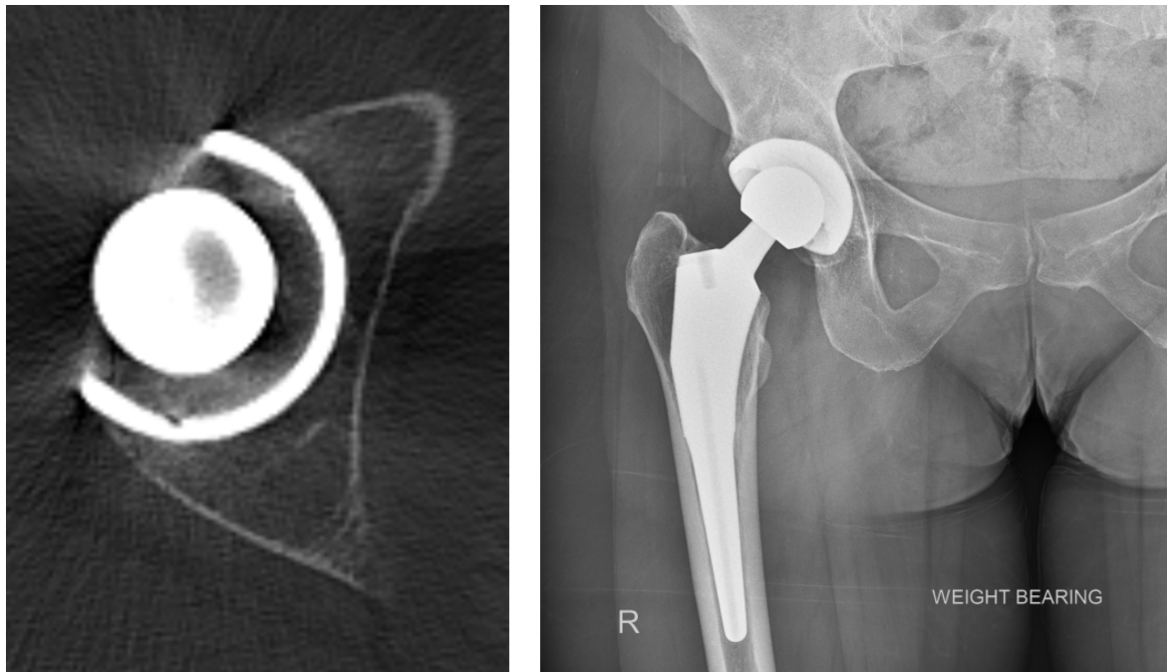


Figure 14 (Left) Cup prominence viewed on a on axial slices of a CT scan. (B) Standing anteroposterior (AP) pelvic radiograph of the same patient. As seen in the AP radiograph, the component appears well fixed and appropriately anteverted. However, upon review of the CT scan, the component can be seen to project beyond the acetabular bony margin.

Treatment of Iliopsoas Tendonitis

Multiple treatments exist for iliopsoas tendonitis manifesting as groin pain, each with its own trade-off between success, invasiveness, and possible complications. These treatments can broadly be classified into two categories: non-operative and operative.¹⁴³

Non-operative management includes physical therapy, non-steroidal anti-inflammatory drugs (NSAIDs), and peritendinous injections of a corticosteroid mix guided by ultrasound or CT.^{125,148–150} A case report describing the use of Botulinum Toxin Type A has also been reported¹⁵¹. However, these treatments yield variable results and typically only provide temporary pain relief.^{125,126,143,152}

Operative management includes iliopsoas tenotomy or tendon debridement, performed either through an open incision or arthroscopically; acetabular cup revision; or both procedures.^{120,126,127,137,143,153}

Dora et al.¹⁴³ reviewed a consecutive series of 29 patients who experienced iliopsoas tendonitis after THA and had previously undergone non-operative management with no improvement in symptoms. Seven of the eight (87.5%) patients who elected to continue non-operative management had no improvement in symptoms. One patient underwent an acetabular revision after 24 months at another institution. Therefore, no patients who continued non-operative management reached a successful outcome in this study. For the six patients who underwent an iliopsoas tenotomy, all had complete relief of symptoms by three months. 14 patients (15 hips)

underwent acetabular cup revision and 13 had relief of symptoms by three months. It should be noted that there was a high rate of complications with the acetabular cup revision group, including trochanteric non-union, anterior dislocation of the hip, superficial wound infection, and several cases of trochanteric bursitis. Additionally, multiple patients complained of weakness with flexion and during functional activities such as getting out of a car or climbing stairs. Interestingly, Nunley et al.¹⁵² found that 21/28 (78%) patients with presumed iliopsoas tendonitis were treated successfully with between one and three fluoroscopically-guided steroid injections. A review by Lachiewicz and Kauk¹²⁰ aggregated the published results of surgical and non-surgical management for iliopsoas tendonitis and found that non-surgical management was successful in only 15/38 (39.5%) hips and surgical management led to successful treatment in 65/71 (91.5%) hips.

An algorithm for the optimal treatment pathway for groin pain after THA has been proposed by the American Academy of Orthopaedic Surgeons (AAOS),¹⁴⁵ which can be seen in Figure 15.¹³⁵ For patients who have undergone THA surgery and present with pain three months after surgery, it is suggested that a historical and physical examination is performed, followed by a referral for the patient to receive an several x-rays and erythrocyte sedimentation rate (ESR) and C-reactive protein (CRP) inflammation biomarker tests to determine whether a prosthetic joint infection (PJI) is present. If the tests come back negative for an infection, a 3-phase bone scan is suggested to determine whether an occult fracture is present. If no fracture is present, it is suggestive of iliopsoas tendonitis and an ultrasound or CT-guided injection of corticosteroid into the sheath of the iliopsoas tendon should be performed. Finally, if pain relief is only temporary, a iliopsoas tenotomy or acetabular revision may be performed.^{135,145}

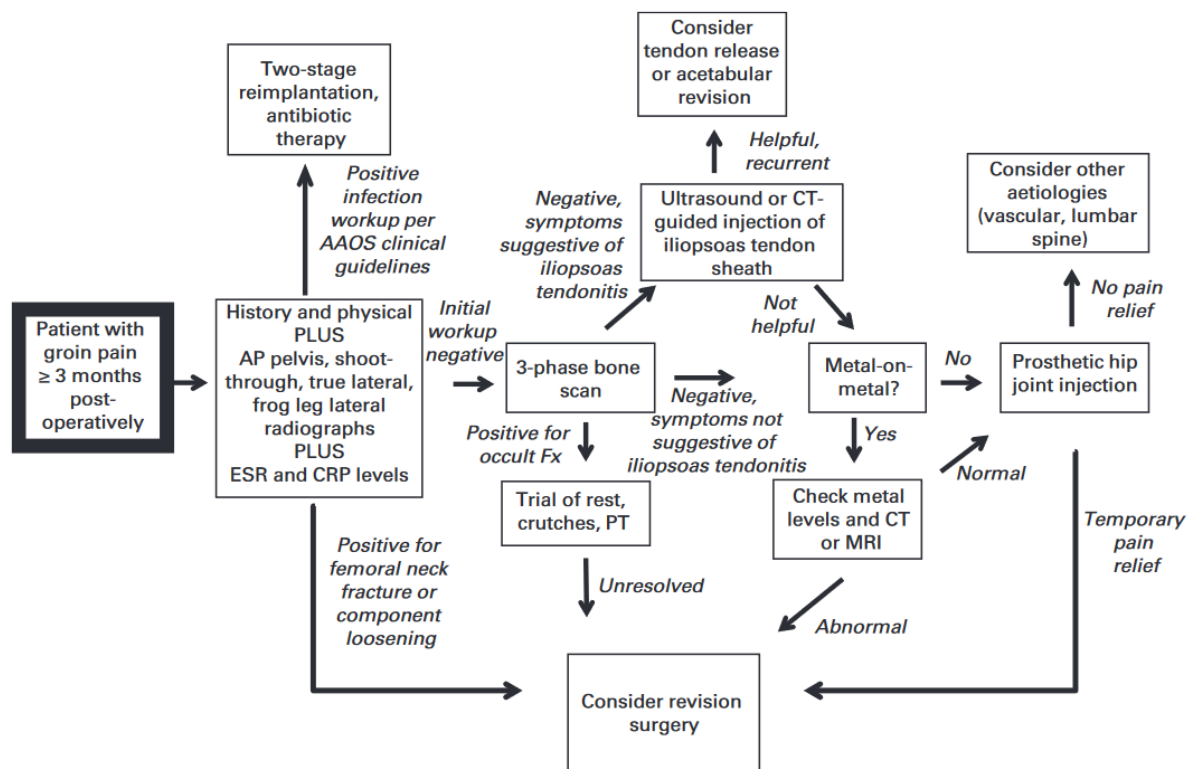


Figure 15 AAOS algorithm for evaluation and treatment of groin pain after THA surgery. AP = anteroposterior, PT = physical therapy, Fx = fracture. Reprinted with permission from the British Editorial Society of Bone & Joint Surgery.

Aetiologies of Iliopsoas Tendonitis

Several causes of iliopsoas tendonitis have been described in the literature. Some causes are less frequent, such as the penetration of fixation screws through the ilium,^{126,128} the extrusion of cement (in cases where cemented acetabular prostheses have been used),¹⁵³ dramatic increases in offset or leg length,¹²⁵ or the overhang of a femoral collar.¹⁵⁴ The more frequently cited causes of iliopsoas irritation are a large diameter femoral head^{129,133,134,138,139} and prominence of the anterior surface of the acetabular cup resulting from retroversion or under-anteversion of the cup, lateralisation of the cup, oversizing of the cup, or anatomy that leaves part of the cup unavoidably exposed.^{126,127,136}

Interestingly, due to the anatomic disadvantage of a shallow acetabulum in dysplastic hips and the subsequent oversizing or retroversion of the component relative to the anatomy, dysplastic patients would theoretically have a greater likelihood of experiencing iliopsoas irritation and groin pain. However, a study by Zhu et al.¹²⁸ that investigated iliopsoas tendonitis in dysplastic patients who underwent THA surgery found no difference in incidence between a dysplastic cohort compared to a control cohort, despite finding a significantly greater number of protruding screws, cups with anterior overhang, and lengthening.

Zhu et al.¹²⁸ provided three reasons for this contradiction between theory and reality. First, despite a greater number of overhanging cups in the dysplastic cohort, the significantly smaller cup sizes (mean of dysplastic cohort = 44.6 ± 2.0 (38–48), mean of control cohort = 47.9 ± 2.8 (44–56)) were not large enough to irritate the iliopsoas tendon. Second, the protruding screws did not perforate severely enough to irritate the iliopsoas. Third, the postoperative leg length discrepancy (LLD) in the dysplastic group was comparable to the preoperative LLD. Fourth, and perhaps most importantly, prophylactic iliopsoas tendon releases were performed in 42.1% of the dysplastic cohort due to muscular contractures that needed releasing to permit sufficient lengthening.

Adding further complexity to the contradiction between theory and reality in the prevalence of iliopsoas tendonitis in dysplastic patients is an in-silico study by Audenaert et al.¹⁵⁵ This study sought to investigate the mechanism of coxa saltans (internal snapping hip) by simulating iliopsoas tendon behaviour in a virtual population of 40,000 anatomies (20,000 males and 20,000 females) and comparing tendon movement during flexion, abduction, and external rotation, and back to neutral. Anatomies at-risk of manifesting as a painful hip from internal snapping hip syndrome were defined as those with excess tendon movement. The authors concluded that increased anteversion, increased valgus, decreased femoral offset, and decreased ischiofemoral distance were the main anatomical phenotypes that resulted in excess tendon movement, which are all common anatomical geometries found in dysplastic population.¹⁵⁶

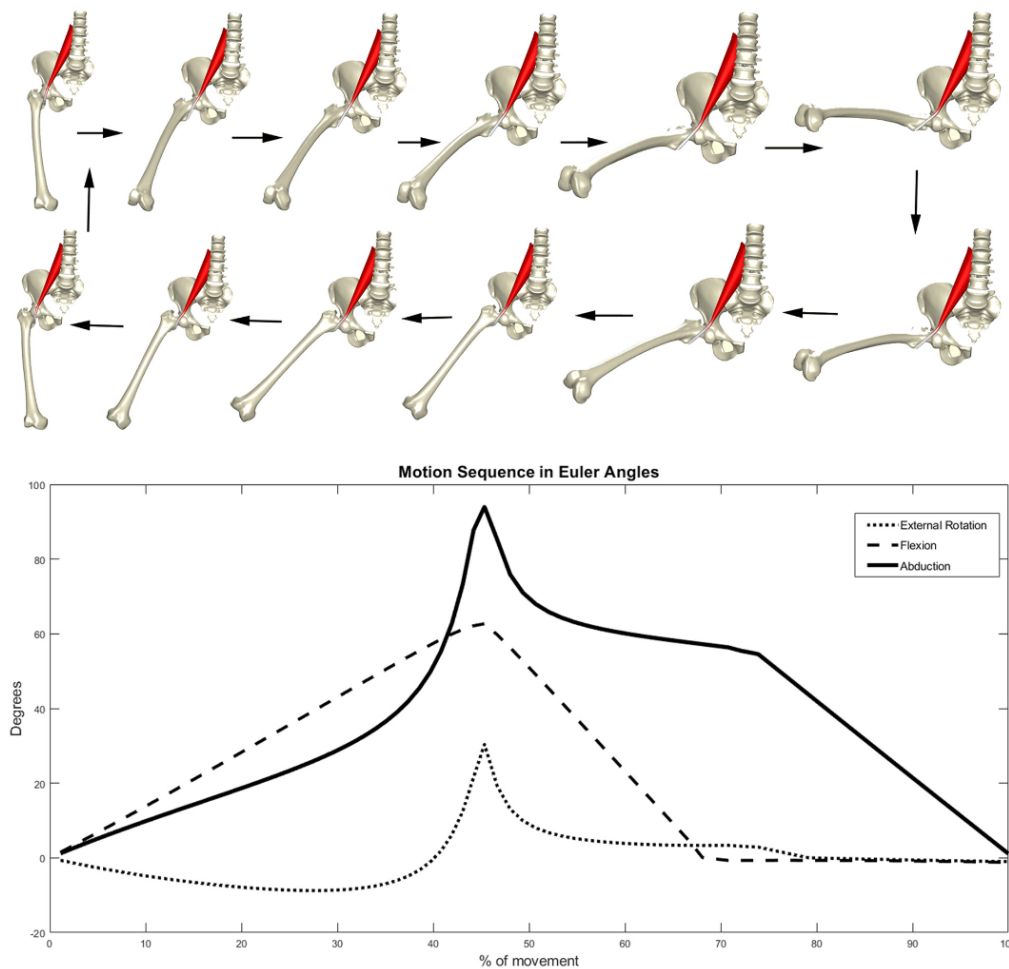


Figure 16 Visual and graphical representation of the individual rotational elements throughout the simulation. The top sequence displays the pelvis, femur, and predicted iliopsoas anatomy in various positions throughout the simulated circumduction, while the bottom quantifies the external rotation, flexion, and abduction in degrees over the course of the motion cycle. Courtesy of Audenaert et al., 2020, *Frontiers in Bioengineering and Biotechnology*. This work is licensed under a Creative Commons Attribution License (CC BY 4.0)

This study by Zhu et al.¹²⁸ also provided evidence for a more recently proposed cause of iliopsoas tendonitis where the iliopsoas is irritated by functioning to stabilise the hip anteriorly due to excessively high acetabular cup anteversion that leads to chronic micro-instability of the prosthetic femoral head.^{157–159} The mechanism of this phenomenon may work as follows: the iliopsoas complex functions as a pulley system with the combined acetabular margin, femoral head, and anterior capsule.¹³⁰ If a THA is performed through the direct anterior approach (DAA), the anterior capsule is excised and subsequently weakened, making the iliopsoas the dominant soft tissue structure for stabilising the hip joint in extension.¹⁶⁰ This may lead the person to internally rotate their femur to prevent anterior instability, tautening the iliopsoas across the acetabular margin of the pelvis and leading to irritation. Similarly, if the acetabular cup is excessively anteverted, posterior prosthetic impingement between the acetabular cup and femoral stem may cause micro-dislocations of the femoral head, causing wear and irritation of the iliopsoas.

Quantifying Iliopsoas Impingement

There has been one previous attempt at modelling the impingement between the iliopsoas and acetabular cup.¹⁴⁶ This study involved implanting six oversized cups into cadaver hips and inserting a thin metal wire in the sheath of the iliopsoas tendon at the level of the LT.

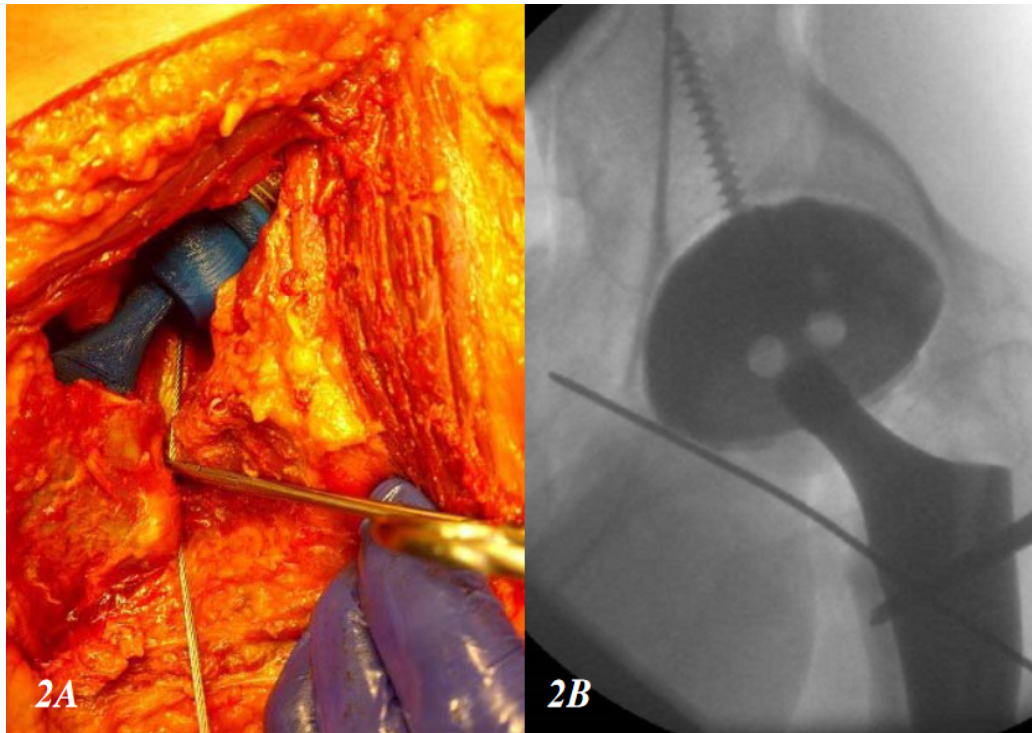


Figure 17 (A) Shows the insertion of the thin wire into the iliopsoas tendon sheath. (B) Shows a fluoroscopic image that demonstrates the position of the wire relative to the implants and the acetabular margin of the pelvis. Courtesy of Ries et al., 2019, Reconstructive Review, Joint Implant Surgery & Research Foundation (JISRF). This work is licensed under a Creative Commons Attribution – Non-Commercial license (CC BY-NC 4.0).

Each cadaver underwent a CT scan, and the data was imported into imaging software for segmentation of the bony and prosthetic geometry. The wire clearance between the iliopsoas and acetabular cup was measured for each hip and the cup orientations and cup type (hemispheric or offset head centre) were varied to determine the influence of cup orientation and cup geometry on the impingement value. The authors concluded that reduced anteversion was strongly correlated with increased impingement, and that implant geometry plays a significant role too.

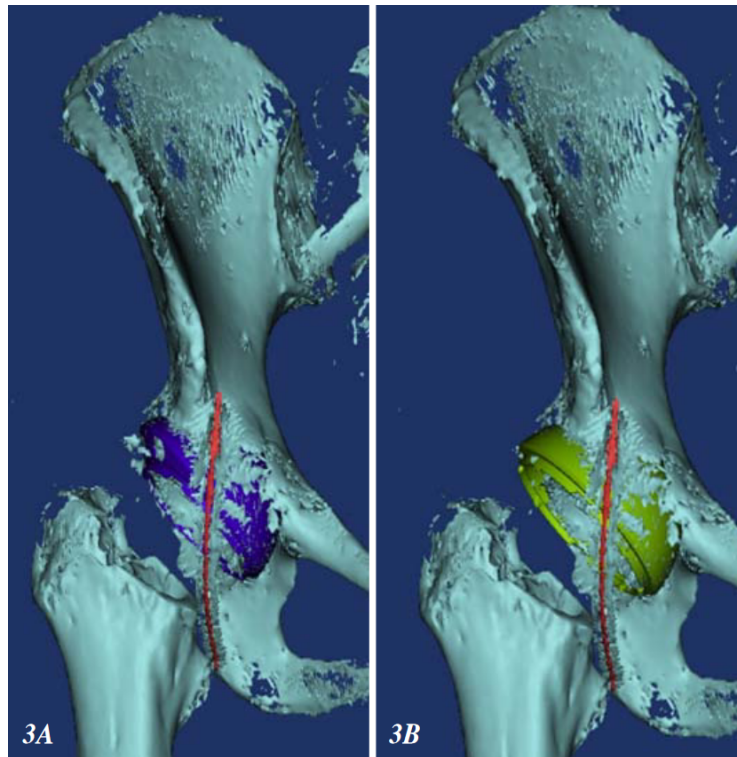


Figure 18 Segmented models of a cadaver's bony and prosthetic anatomy, in addition to the metal wire inserted into the iliopsoas tendon sheath. The image on the left contains the offset head centre acetabular cup and the image on the right shows the hemispherical cup. Courtesy of Ries et al., 2019, Reconstructive Review, Joint Implant Surgery & Research Foundation (JISRF). This work is licensed under a Creative Commons Attribution – Non-Commercial license (CC BY-NC 4.0).

However, this cadaveric study was not without limitations. First, being a cadaveric study, there was no understanding whether the impingement between the iliopsoas and acetabular cups would actually manifest as groin pain. Second, impingement, which is the rubbing or pressure on a soft tissue structure from an adjacent structure, was simplified as the straight-line wire clearance between the acetabular cup and iliopsoas. Third, the iliopsoas, which is a large delta-shaped muscle, was approximated as a thin cable. Fourth, the impingement was measured with the patient's anatomy oriented in a supine position and, therefore, these results may differ when a person is in their functional, weight-bearing stance. Fifth, being a cadaveric study, the bony anatomy were likely positioned in unrealistic orientations due to changes in soft tissue tensioning.

LITERATURE REVIEW CONCLUSIONS

AND

THESIS OUTLINE

Total hip arthroplasty surgery is a highly successful operation.^{41,161} However, despite its success, complications remain, including dislocation, infection, loosening, and soft tissue complications, such as greater trochanteric pain syndrome and iliopsoas tendonitis.^{112,120} Postoperative iliopsoas tendonitis manifests as groin pain that is exacerbated by activities of daily living, particularly movements involving active flexion at the hip.¹²⁰

Diagnosis of iliopsoas tendonitis varies between clinicians, but typically involves taking the patient's history and performing a clinical examination. Clinicians will wait for a period of three months to pass after surgery to ensure any residual pain from surgery has had time to settle and then assess the patient in active flexion and extension positions to localise the source of pain. After a clinical diagnosis of iliopsoas-related groin pain, the patient may be referred for imaging and diagnostic studies, such as anteroposterior or lateral radiographs, ultrasound, or computed tomography.^{112,120,125,162}

Multiple sources of iliopsoas tendonitis have been described in the literature, including large diameter femoral heads,^{129,133,134,138} excessive lengthening or offset added intraoperatively,¹²⁵ and protruding screws or bone cement^{128,143}. However, iliopsoas tendonitis is most frequently attributed to an exposed anterior surface of the acetabular cup impinging on the iliopsoas, leading to irritation, inflammation, and pain.^{126,127,136}

To treat iliopsoas tendonitis, conservative management is recommended first, which involves physical therapy and non-steroidal anti-inflammatory drugs. If the groin pain persists, the clinician may recommend corticosteroid injections, which function both as a pain management and diagnostic tool. If pain persists further, the clinician may recommend further injections, or provide the patient with surgical treatment options, such as iliopsoas tenotomy, revision of the acetabular component, or both.^{112,120,143,162} Iliopsoas tenotomies are less invasive procedures that can be performed arthroscopically and have lower complication rates, whereas acetabular cup revisions carry greater chance of complications, but also remove the source of pain – the exposed edge of the acetabular cup – and minimise damage to the function of the patient's iliopsoas muscle.^{143,162}

Iliopsoas is reported to be between 4-30% of patients after total hip arthroplasty,^{125,126,128-132} and 18-30% of patients after hip resurfacing arthroplasty.^{129,132,134} Despite its relatively high incidence, and the burden on patient's life by reducing the function of their artificial hip, iliopsoas tendonitis remains under-studied. Most studies concerning iliopsoas tendonitis after hip arthroplasty surgery

are either case studies of patients that report on the diagnosis and treatment pathway for a relatively small sample of patients, or retrospectively review a single surgeon's database to determine an approximate rate of incidence.^{125,126,130}

One previous study has attempted to quantify iliopsoas impingement.¹⁴⁶ However, this study was performed on cadavers and had several limitations. First, due to the nature of this cadaveric study, there was no understanding of whether the impingement between the acetabular cup and iliopsoas would result in irritation and pain. Second, the authors simplified the anatomy of the iliopsoas by inserting a small wire into the iliopsoas and using a simple measure, wire clearance, as a proxy for iliopsoas impingement to assess differences between cup orientations. Finally, there was no understanding of functional changes between positions, in addition to limitations associated with cadaveric anatomy potentially being oriented in a significantly different position than would be observed in-vivo.

As far as the author is aware, there are no published studies that attempt to simulate iliopsoas impingement to study iliopsoas tendonitis with the potential application of contributing to a preoperative total hip arthroplasty planning protocol for optimised component orientations. Therefore, one aim of this thesis is to develop a simulation that can quantify impingement between the acetabular cup and iliopsoas using an algorithm to approximate the iliopsoas wrapping path. The simulation will be intended for utilisation in conjunction with other simulations, such as range of motion simulations, to optimise preoperative planning for total hip arthroplasty and hip resurfacing arthroplasty by predicting a risk of iliopsoas tendonitis on a patient-specific level at the preoperative planning stage. As such, the simulation needs to execute quickly and use inputs that are already available in a preoperative planning workflow. For example, frequently available data includes segmented three-dimensional models of patients' bony anatomy in *.stl* format and three-dimensional coordinates that indicate relevant bony or soft tissue landmarks, such as the insertion points of muscles.

The initial chapters of this dissertation will focus on development and assessment of the iliopsoas impingement detection simulation by modelling iliopsoas impingement in a representative samples of patients with total hip and hip resurfacing arthroplasties. Assessment of the simulation's accuracy will be enabled by comparing the iliopsoas impingement between symptomatic and asymptomatic cohorts where the symptomatic cohort will be comprised of patients who were diagnosed with iliopsoas tendonitis postoperatively and the asymptomatic patients will be comprised of patient not diagnosed with iliopsoas tendonitis.

If the simulation is observed to have high sensitivity and specificity to iliopsoas tendonitis, investigations will be conducted in the preoperative context to determine other factors that may exacerbate iliopsoas tendonitis, such as the patient's functional posture, and which factors influence impingement more; acetabular cup orientation or position. These chapters that study the

simulation in the preoperative context will assist in determining other preoperative factors that can be used as warnings to clinicians of patients with an increased risk of iliopsoas tendonitis, in addition to data on the best methods of ameliorating or reducing the risk of iliopsoas tendonitis.

Finally, a chapter will be devoted to discussing the overall results of the dissertation, the implications of this research, and unanswered questions. It is anticipated that some of the unanswered questions will be related to patients who were diagnosed with, and treated for, iliopsoas tendonitis, but for whom no iliopsoas impingement was detected. It is likely that these patients will have experienced iliopsoas irritation from one of the other sources of tendonitis, and it will be important to discuss these patients individually to understand if their tendonitis was predictable, and whether there are any patterns that emerge amongst these patients, such as previous arthroscopic surgeries, which could also be used as inputs into the preoperative iliopsoas prediction.

CHAPTER 2: ILIOPSOAS TENDONITIS AFTER TOTAL HIP ARTHROPLASTY: AN IMPROVED DETECTION METHOD WITH APPLICATIONS TO PREOPERATIVE PLANNING

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Abstract

INTRODUCTION: There are several reasons a patient may experience pain after total hip arthroplasty (THA) including infection, incorrect indication, instability, or soft tissue complications, such as iliopsoas tendonitis. Despite a relatively high incidence, occurring in 4-30% of patients after undergoing hip arthroplasty, there are few attempts at modelling the impingement between the iliopsoas and acetabular cup, and no attempts at modelling this in a representative cohort of subjects. The purpose of this study was to develop a novel computational model for quantifying the impingement between the iliopsoas and acetabular cup and assess its utility in a case-controlled investigation.

METHODS: This was a retrospective cohort study of patients who underwent THA surgery that included 23 symptomatic patients diagnosed with iliopsoas tendonitis and 23 patients not diagnosed with iliopsoas tendonitis. All patients received postoperative computed tomography (CT) imaging, postoperative standing radiography, and had minimum 6 months' follow-up. Exclusion criteria included resurfacings, metal-on-metal implants, and dual mobility cups. 3D models of each patient's prosthetic and bony anatomy were generated, landmarked, and simulated in a novel iliopsoas impingement detection model in supine and standing pelvic positions. Logistic regression models were implemented to determine if the probability of pain could be significantly predicted. Receiver operating characteristic (ROC) curves were generated to determine the model's sensitivity, specificity, and area under the curve (AUC).

RESULTS: Highly significant differences between the symptomatic and asymptomatic cohorts were observed for iliopsoas impingement. Logistic regression models determined that the impingement values significantly predicted the probability of groin pain. The simulation had a sensitivity 74%, specificity of 100%, and an AUC of 0.86.

DISCUSSION: Using one of the largest samples of patients who have been diagnosed with iliopsoas tendonitis after THA, it was demonstrated that the novel simulation could detect impingement between the iliopsoas and cup through a retrospective, case-controlled investigation. This was demonstrated with the symptomatic patients exhibiting significantly greater levels of impingement than the asymptomatic patients. Other noteworthy findings included: (1) symptomatic patients with little-to-no impingement, indicating the multicausal nature of iliopsoas tendonitis; (2) no impingement observed in some asymptomatic patients who also had high cup prominence values, indicating the simulation can differentiate between cup prominence that results in impingement and cup prominence that does not; (3) minor impingement detected in some asymptomatic patients, which may indicate a threshold for irritation or pain. In conclusion, this tool has the potential to be used preoperatively, to guide decisions about optimal cup placement, and postoperatively, to assist in the diagnosis of iliopsoas tendonitis and determine an appropriate treatment pathway.

Introduction

With its low revision rates, total hip arthroplasty (THA) is broadly viewed as a highly successful operation for relieving pain and restoring mobility after osteoarthritis (OA) of the hip.⁴¹ However, revision rates do not provide a holistic understanding of patient outcomes as they do not capture postoperative pain or dissatisfaction rates,^{44,46} which may persist for several reasons.¹²⁸ These include infection, instability, or soft tissue complications,¹²⁸ such as greater trochanteric pain syndrome and iliopsoas tendonitis.¹¹² Iliopsoas tendonitis can occur due to protruding screws or cement^{128,143} excessive increases in offset or leg lengthening,¹²⁵ an overhanging femoral collar,¹⁵⁴ or large diameter femoral heads.^{129,133,134,138,139} However, it is most frequently attributed to an anteriorly exposed acetabular cup resulting from retroversion, lateralization, or oversizing of the component.^{126,127,136}

The incidence of iliopsoas tendonitis and postoperative groin pain is reported to be up to 29% of patients after THA^{125,126,128–132} and up to 32% of patients after hip resurfacing arthroplasty (HRA).^{129,132,134} It should be noted that several of the most frequently cited papers investigating the incidence of iliopsoas impingement after THA have found the incidence to be below 5%.^{125,126,130} However, these studies were limited by small samples of symptomatic patients,^{125,126,130} were retrospective,^{125,126,130} and are now two decades old.^{125,126} Large variability in rates of reported incidence may be explained by the heterogeneity in regards to the duration of follow-up and varying criteria of pain for inclusion.¹³⁵ Therefore, it may be that the true and current incidence of iliopsoas impingement is unknown, particularly given the widespread adoption of larger diameter femoral heads and different surgical approaches in recent years.^{138–140,163}

Despite its relatively high incidence, iliopsoas tendonitis is difficult to diagnose with certainty, can require multiple iterations of treatment, and is lacking in attempts to computationally model. As far as the authors are aware, only one previous study has attempted to quantify impingement between the iliopsoas and cup.¹⁴⁶ This in-vitro cadaveric study concluded that impingement increased as cup anteversion decreased and offset head centre cups with anterior recess reduced iliopsoas impingement.¹⁴⁶ However, being a cadaveric study, it had several limitations. First, the authors could not determine whether the impingement between the iliopsoas and acetabular cup would result in irritation and groin pain. Second, the iliopsoas was simplified as a single wire and wire clearance was used as a proxy for impingement. Finally, the study did not assess if, and by how much, the impingement altered in functional positions.

We sought to develop an in-silico model that could quantify impingement between the acetabular cup and iliopsoas and then assess its utility by simulating impingement in a case-controlled investigation of symptomatic and asymptomatic patients. The secondary aim was to identify anatomical and surgical parameters that correlate with impingement. Our primary hypothesis was that the simulation, using anatomic and kinematic information about the pelvis, femur, and

acetabular cup, would detect a significantly greater level of iliopsoas impingement in the symptomatic cohort. Our secondary hypothesis was that the simulation would be a better predictor of iliopsoas tendonitis than the traditional cup prominence measurement.

Patients and Methods

This was a retrospective cohort study comparing iliopsoas impingement between a cohort of symptomatic patients who were diagnosed with iliopsoas tendonitis after THA surgery and a cohort of asymptomatic patients who were not diagnosed with iliopsoas tendonitis after THA. The primary outcome was a difference in detected impingement values. Secondary outcomes were differences in cup prominence, cup size, pelvic tilt, and cup orientation. This retrospective study was approved by the Bellberry Human Research Ethics Committee (study number 201203710).

Patient Population

A retrospective search for THA patients who were diagnosed with iliopsoas tendonitis was conducted in two experienced surgeons' databases. Inclusion criteria were that patients had undergone primary total hip replacement with a postoperative computed tomography (CT) imaging, postoperative standing x-ray, minimum 6 months' follow-up, and to have a hemispherical acetabular cup implanted. Exclusion criteria included hip resurfacing implants, metal-on-metal (MoM) implants, and dual mobility cups. After application of inclusion and exclusion criteria to these database searches, 23 patients remained. The details of this patient cohort can be found in Table 3.

Table 3 Deidentified details of the symptomatic patient cohort, including age, gender, implant sizes, method of diagnosing iliopsoas tendonitis, and the treatment the patient underwent.

Patient ID	Surgeon	Age	Gender	Side	Cup Size	Head Size	Diagnosis	Treatment
1	1	98	F	Right	50	32	Active hip flexion test	Cortisone injections and iliopsoas release
2	1	73	F	Right	50	28	Active hip flexion test	Cortisone injection
3	1	70	M	Right	62	48	Active hip flexion test	Cortisone injection
4	1	63	F	Left	50	36	Active hip flexion test	Cortisone injection and iliopsoas release
5	1	68	F	Left	48	32	Active hip flexion test	Cortisone injection and iliopsoas release
6	1	83	F	Right	48	36	Active hip flexion test	Cortisone injections and iliopsoas drainage
7	1	78	M	Left	54	36	Active hip flexion test	Cortisone injection
8	1	61	F	Left	56	28	Active hip flexion test	Cortisone injection
9	1	76	M	Right	58	28	Active hip flexion test	Cortisone injection and iliopsoas release
10	1	57	M	Right	58	48	Active hip flexion test	Cortisone injection
11	1	72	F	Left	48	28	Active hip flexion test	Iliopsoas release
12	1	75	M	Left	60	48	Active hip flexion test	Cortisone injection
13	1	79	F	Right	52	32	Active hip flexion test	Cortisone injection
14	1	61	F	Right	48	32	Active hip flexion test	Cortisone injection
15	2	49	F	Left	52	36	Pain in extension, bicycle test	Cup revision
16	2	51	F	Right	48	32	Pain in flexion, bicycle test	Conservative treatment, including physiotherapy
17	2	53	F	Left	52	36	Pain in flexion,	Cup and stem revision

							bicycle test	
18	2	41	F	Left	50	42	Pain in flexion and extension, bicycle test	Cup revision and iliopsoas release
19	2	63	F	Left	54	36	Pain in flexion, bicycle test	Iliopsoas release with cup revision planned
20	2	46	F	Left	48	40	Pain in flexion, bicycle test	Conservative treatment, including physiotherapy
21	2	26	F	Right	48	36	Pain in flexion, bicycle test	Iliopsoas tenotomy
22	2	64	M	Right	54	36	Pain in flexion, bicycle test	Iliopsoas tenotomy
23	2	39	F	Left	48	36	Pain in flexion, bicycle test	Iliopsoas tenotomy

The asymptomatic cohort similarly consisted of 23 patients. 14 of these patients were randomly selected from Surgeon 1's database of patients after ensuring that they were not diagnosed with postoperative iliopsoas tendonitis and met the inclusion and exclusion criteria. The remaining 9 patients were randomly selected from a database of patients referred to 360 Med Care for postoperative THA analysis for non-groin pain related causes ensuring they also met the inclusion and exclusion criteria. A flow chart of the retrospective cohort selection process can be found in Figure 19.

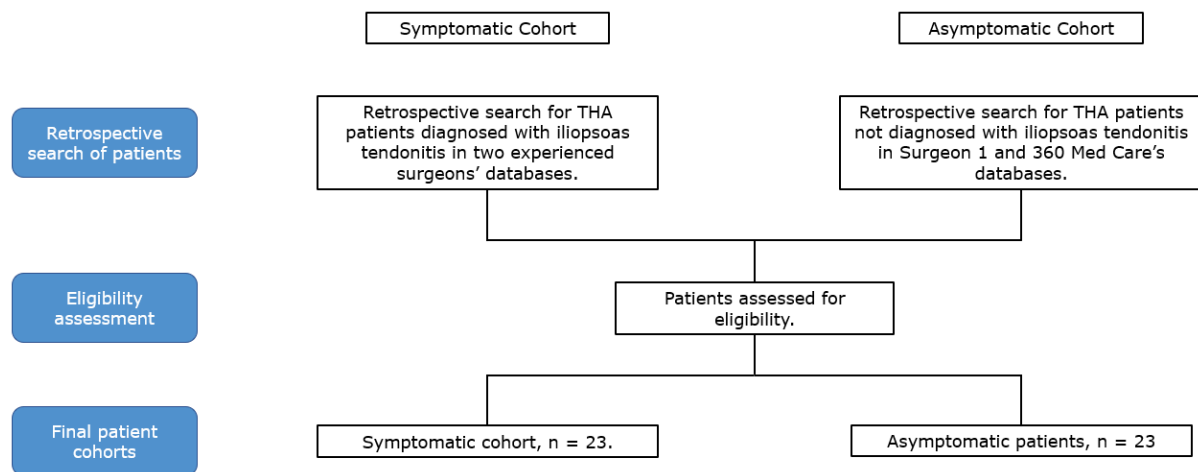


Figure 19 Flow chart of the patient selection process for the symptomatic cohort, which includes patients who were diagnosed with iliopsoas tendonitis, and asymptomatic cohort, which includes patients that were not diagnosed with iliopsoas tendonitis. Reprinted with permission from the British Editorial Society of Bone & Joint Surgery.

Diagnosis of Iliopsoas Tendonitis

Prior to both surgeons' clinical examination and diagnosis of iliopsoas tendonitis, a patient history was taken with patients indicating groin pain with active hip flexion activities, such pain lifting the leg on to a bed or into a car. Patients also often reported groin pain with sneezing or coughing.

Diagnosis for Surgeon 1 was confirmed via the active hip flexion test in supine. Diagnostic criteria included no pain at rest, no pain with passive flexion of 10° , and pain with active flexion of 10° with a straight leg raise. The same tests were performed in seated without flexion as a secondary confirmation.

Diagnosis of iliopsoas tendonitis for Surgeon 2 was similarly confirmed via clinical examination of the patient. Pain at flexion in a bicycle test indicated anterior impingement between the iliopsoas and acetabular cup leading to inflammation. Pain from an apprehension test (extension and external rotation) or at extension in the bicycle test indicated the iliopsoas may be functioning as an anterior stabiliser to the hip joint, causing overuse and irritation of the iliopsoas.

Generation of 3D models of the Bony Anatomy and Prostheses

All CT scans had a Z-direction pixel thickness of 1.25-1.5mm and in-plane resolution of 0.8-1mm x 0.8-1mm. Segmenting and landmarking was performed in ScanIP R-2020.09 (Synopsys, California, USA) to generate 3D models of the patients' bony anatomy and prostheses with quality checks of the segmentation and landmarks by qualified surgical planning engineers to ensure accuracy.

Segmentation was performed semi-automatically using in-built functions augmented with manual segmentation to finalise the models. Specifically, the preoperative pelvic CT scans were imported into ScanIP, which produces a histogram of the scan by measuring the Hounsfield Unit (HU) of individual pixels. The full HU range of the scan was imported and copies of the background were created with altered thresholds to isolate the bony anatomy and the prosthetic implants. Masks of the pelvis and ipsilateral proximal femur were then generated using the 'Floodfill' tool on the background that isolated the bony tissue. These masks were filled, edited, inspected, and exported as .stl files, providing detailed 3D surface geometry of the patient's relevant bony anatomy. A similar process was followed to generate masks of the prosthetic implants by the background that isolated the prosthetic implants. Additionally, to reduce inaccuracies associated with flare in the CT, distorting the segmented models of the prosthetic implants, correctly sized manufacturer-issued .stl files of the implants were imported into ScanIP and registered to their corresponding positions in the CT scan. This registration and alignment process involved meticulously checking the position of the manufacturer-issued .stl file against the CT scan in all three planes (coronal, axial, and sagittal) and the masks viewed in 3D to determine its final position. After the positioning of implants was complete, they were exported as .stl files.

Landmarking of the Bony Anatomy and Prostheses

Landmarks (Figure 20) were taken manually of the patient's left and right anterior superior iliac spine (ASIS), left and right pubic symphysis (PS), the femoral head centre (FHC), three superior iliopsoas attachment sites, and one inferior iliopsoas attachment site. Landmarking of the FHC involved use of a custom plug-in that uses three points to generate a sphere, with the centre of the sphere being the FHC. The three points of the sphere were locations on the edge of the femoral head, at different heights. The ASIS and PS points were taken to determine the patient's anterior pelvic plane (APP), which was used to measure their supine pelvic tilt and reference the cup orientation to. The iliopsoas insertion sites included one point on the lateral superior plateau of the patient's L5 vertebrae, the lateral-most point on the patient's L5 transverse process, a point approximately 3-5mm's lateral of the patient's sacroiliac joint, and the medial-most point of the patient's lesser trochanter (LT).

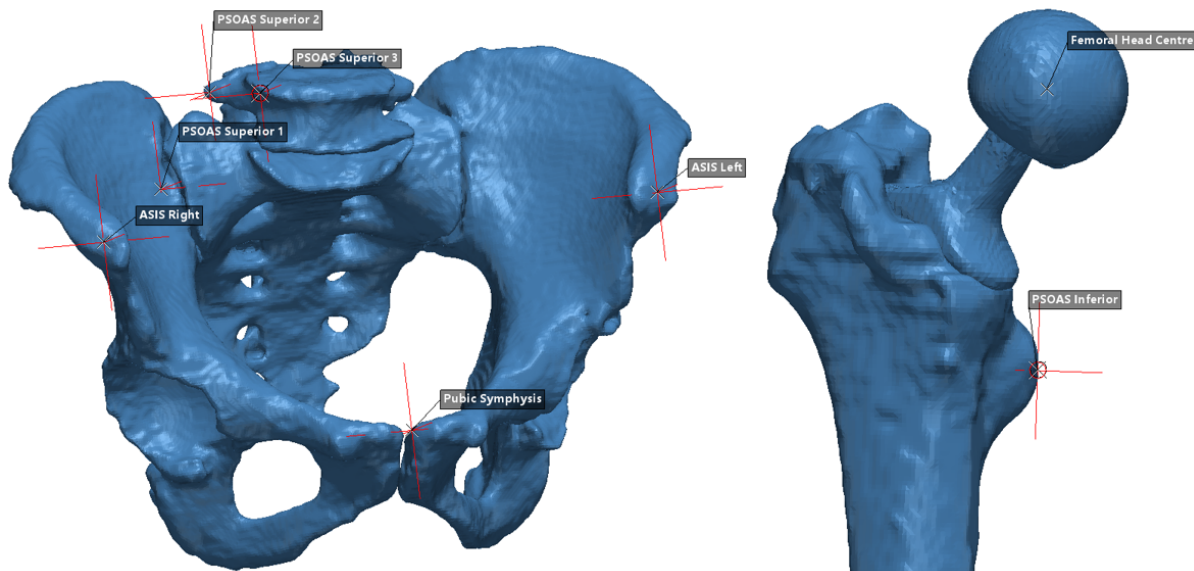


Figure 20 Illustration of the landmarks taken for the simulation. The ASIS points and pubic symphysis form the anterior pelvic plane (APP) and allow calculation of the supine pelvic tilt. Psoas Superior 1-3 and Psoas Inferior represent the 'attachment sites' of the iliopsoas. The Femoral Head Centre was used as the point at which the pelvis rotates around. Reprinted with permission from the British Editorial Society of Bone & Joint Surgery.

Simulating Iliopsoas Impingement

The simulation, which was developed in R Studio v1.3.1903 (Boston, MA, USA), began by importing the bony and prosthetic 3D models in their supine (CT) positions. A representation of the iliopsoas was generated using a novel approach by tracing the shortest path from each superior attachment site around the acetabular margin of the pelvis to the inferior insertion point. The approach to generating the trace of the iliopsoas involved several steps. First, a plane was created using the superior insertion point, the inferior insertion point (at the LT), and an additional point in space near the superior insertion point but offset in the y-axis. This plane was then intersected with the 3D meshes using an in-built function in R; `meshPlaneIntersect`. The output of this function was a three-column matrix consisting of the points of intersection between the meshes and the plane. A convex hull was then applied to the three-column matrix to determine the shortest wrapping path. This returned a filtered down matrix that included only the x, y, z coordinates of the points that lie on the convex hull. Further filtering was applied to the data to ensure only points that created a wrapping path from the superior insertion point to the inferior point, passing around the anterior pelvic margin, were included.

The three superior insertion points created three distinct wrapping segments. Three segments was chosen as this provided a reproducible and accurate representation of the width of the iliopsoas and the location it passes over the acetabular margin.¹⁶⁴ Additionally, initial testing revealed that three points would repeatedly capture impingement towards the antero-superior edge of the acetabular cup, the antero-inferior edge of the acetabular cup, and around the central anterior

edge of the acetabular cup. Each segment was comprised of two paths; a green path and a red path. The green path did not include the acetabular cup, and the red path did. Impingement, which could be considered the 'stretch' of the iliopsoas due to the acetabular cup, was calculated as the difference in lengths of the green and red paths for each segment (Figure 21). Therefore, in cases with no iliopsoas impingement, the path lengths were equal length. In cases with impingement, the red path was lengthened relative to the green path. Three separate impingement values (one for each segment) were calculated in supine and reported as the mean and maximum of these values; supine mean impingement and supine maximum impingement.

The pelvis was then rotated to its standing pelvic orientation using the difference in supine and standing pelvic tilts. For example, if the supine pelvic tilt was measured to be 3° of anterior tilt and the standing pelvic tilt was measured to be 5° of posterior tilt, the pelvis would be rotated posteriorly by 8°. Similarly, if the supine pelvic tilt was measured to be 6° of posterior tilt and the standing pelvic tilt was measured to be 4° of anterior tilt, the pelvis would be rotated anteriorly by 10°. Following this rotation, the same impingement detection algorithm described above was performed and the standing impingement values were reported as standing mean impingement and standing maximum impingement.

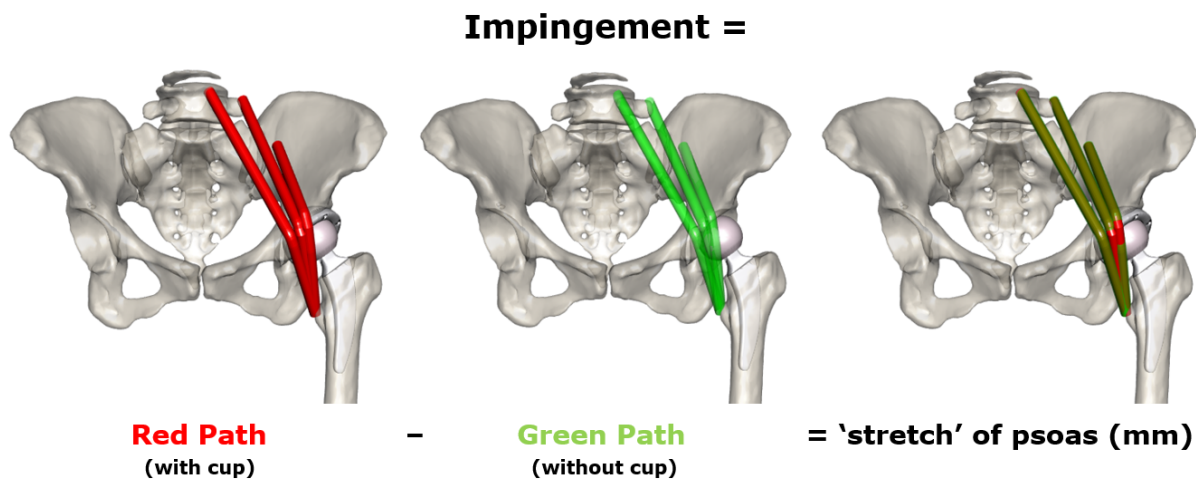


Figure 21 Schematic of the iliopsoas impingement simulation in a patient's standing pelvic position. Three segments were chosen as they approximate the width of the iliopsoas and the location it passes over the acetabular margin. These segments are comprised of two paths; a green and a red path. The green path does not include the cup and the red path does. The difference between these paths is equal to the impingement and could be considered the 'stretch' of the iliopsoas due to the cup. Reprinted with permission from the British Editorial Society of Bone & Joint Surgery.

Calculating Cup Prominence

Cup prominence was measured using the same method proposed by Cyteval and Sarraière et al.¹⁴⁷ as the most protruded length of acetabular cup that was exposed anteriorly on 2D CT images in the axial plane.

Statistical Analysis and Power Calculation

Statistical analysis was performed in R Studio. An alpha value of 0.05 was used to determine clinical significance. Two-way Student's T-Tests were used to determine significant difference for continuous variables and Chi-Squared tests for categorical variables. Logistic regression models were used to test if cup prominence, standing mean impingement, standing maximum impingement values predicted the probability of iliopsoas tendonitis. Receiver operator characteristic (ROC) curves were generated to determine the simulation's area under the curve (AUC) and optimal predictive threshold for sensitivity and specificity. A post-hoc power calculation with an alpha of 0.05 determined that samples of 23 patients in each cohort had a power of 95% to detect a difference in impingement of 0.3mm, with a standard deviation of 0.4mm. The final sample sizes were therefore deemed sufficient.

Results

No statistically significant difference between symptomatic and asymptomatic cohorts was found for cup anteversion, cup inclination, cup size, femoral head size, supine pelvic tilt, or standing pelvic tilt (Table 4). The mean cup prominence for the symptomatic cohort was 9.1mm ($\pm$ 3.9mm) and 5.7mm ($\pm$ 4.0mm) for the asymptomatic cohort. The difference was statistically significant ($p = 0.006$) (Figure 22).

Table 4 Implant, patient, cup prominence, and iliopsoas impingement results for both cohorts of patients. n.s = not significant, † = Student's T-Test, ‡ = Chi-Squared Test.

Table 2	Cohort	Mean	Range	Standard Deviation	p-Value
APP Inclination	Symptomatic	43.4	30.3 – 59.5	7.1	n.s†
	Asymptomatic	42.7	34.1 – 55.2	4.9	
APP Anteversion	Symptomatic	18.0	-16.4 – 45.0	11.3	n.s†
	Asymptomatic	20.0	1.4 – 36.3	8.0	
Supine Pelvic Tilt	Symptomatic	2.1	-15.1 – 15.5	7.2	n.s†
	Asymptomatic	2.7	-6.0 – 9.4	4.0	
Standing Pelvic Tilt	Symptomatic	-3.3	-19.8 – 13.3	7.9	n.s†
	Asymptomatic	-4.5	-14.8 – 3.3	4.7	
Head Size	Symptomatic	35.7	28 – 48	6.1	n.s‡
	Asymptomatic	33.5	22 – 36	3.4	
Cup Size	Symptomatic	52.0	48 – 62	4.3	n.s‡
	Asymptomatic	51.7	48 – 60	3.2	
Cup Prominence	Symptomatic	9.1	0 – 18.5	3.9	0.006†
	Asymptomatic	5.7	0 – 13.1	4.0	
Supine Mean Impingement	Symptomatic	0.3	0.0 – 1.8	0.4	0.001†
	Asymptomatic	0.0	0.0 – 0.1	0.0	
Standing Mean Impingement	Symptomatic	0.4	0.0 – 2.1	0.5	0.001†
	Asymptomatic	0.0	0.0 – 0.1	0.0	
Supine Maximum Impingement	Symptomatic	0.7	0.0 – 3.7	0.8	0.002†
	Asymptomatic	0.0	0.0 – 0.2	0.0	
Standing Maximum Impingement	Symptomatic	0.7	0.0 – 4.2	0.9	0.001†
	Asymptomatic	0.0	0.0 – 0.2	0.0	

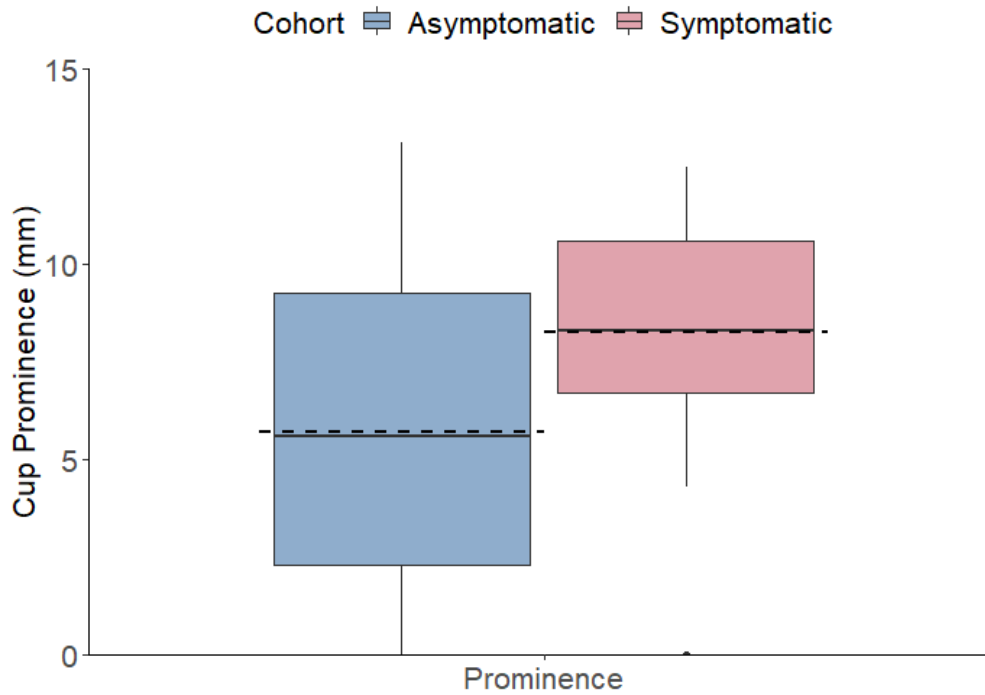


Figure 22 Cup prominence results for the symptomatic and asymptomatic cohorts. The symptomatic cohort had significantly greater cup prominence values. The edges of the box represent the 25th and 75th percentiles, the solid line within the box represents the median, the dashed line represents the mean, the lines represent the ranges, and the dots represent the outliers. Reprinted with permission from the British Editorial Society of Bone & Joint Surgery.

The average supine mean impingement for the symptomatic cohort was 0.3mm ($\pm$ 0.4mm) and 0.0mm ($\pm$ 0.0mm) for the asymptomatic cohort. The difference was statistically significant ($p = 0.001$). The average standing mean impingement for the symptomatic cohort was 0.4mm ($\pm$ 0.5mm) and 0.0mm ($\pm$ 0.0mm) for the asymptomatic cohort. The difference was statistically significant ($p = 0.001$). The average supine maximum impingement for the symptomatic cohort was 0.7mm ($\pm$ 0.8mm) and 0.0mm ($\pm$ 0.0mm) for the asymptomatic cohort. The difference was statistically significant ($p = 0.001$). The average standing maximum impingement for the symptomatic cohort was 0.7mm ($\pm$ 0.9mm) and 0.0mm ($\pm$ 0.0mm) for the asymptomatic cohort. The difference was statistically significant ($p = 0.001$) (Figure 23).

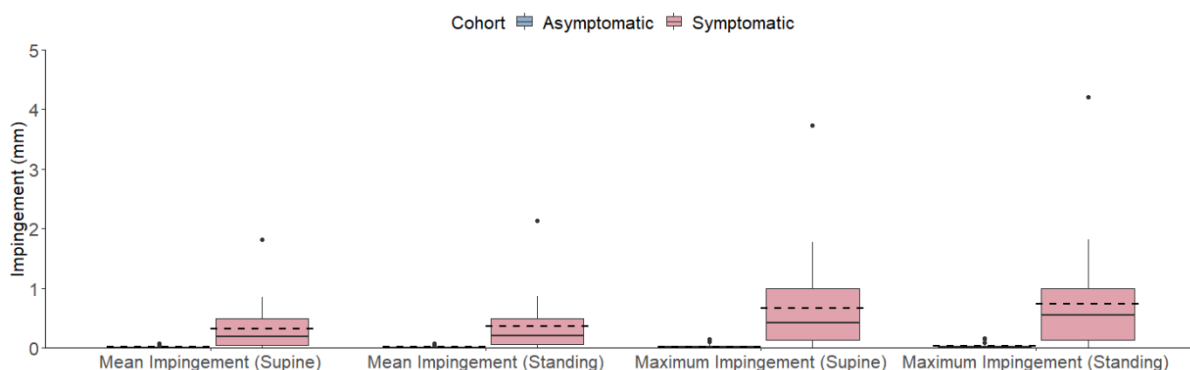


Figure 23 Mean and maximum impingement results for the symptomatic and asymptomatic cohorts in supine and standing positions. The symptomatic cohort had significantly greater mean and maximum impingement values in both standing and supine. Reprinted with permission from the British Editorial Society of Bone & Joint Surgery.

Cup prominence significantly predicted the probability of iliopsoas tendonitis in a logistic regression model ($p < 0.05$) (Table 5). The optimal cut-off point for cup prominence as a predictor of iliopsoas tendonitis was 6.50mm. Using this cut-off point, the logistic regression model showed a sensitivity of 83%, specificity of 57%, and an AUC of 0.72 (Figure 24).

Table 5 Logistic regression model for predicting the probability of iliopsoas tendonitis with cup prominence.

Parameter	Standard Error	Coefficient	p-value
(intercept)	0.75	-1.68	0.03
Cup Prominence	0.09	0.23	0.01

Standing mean impingement and standing maximum impingement significantly predicted the probability of iliopsoas tendonitis in logistic regression models ($p < 0.05$) (Figure 25, Table 6, Table 7). The optimal cut-off point for mean impingement as a predictor of iliopsoas tendonitis was 0.04mm. Using this cut-off point, the logistic regression model showed a sensitivity of 78%, specificity of 91%, and an AUC of 0.86 (Figure 26). The optimal cut-off point for maximum impingement as a predictor of iliopsoas tendonitis was 0.16mm. Using this cut-off point, the logistic regression model showed a sensitivity of 74%, specificity of 100%, and an AUC of 0.86 (Figure 26).

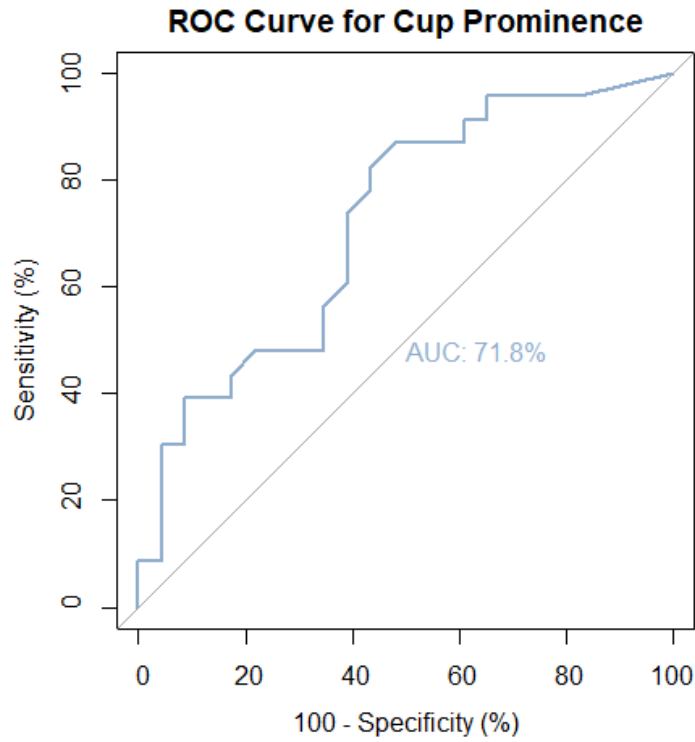


Figure 24 Receiver operating characteristic (ROC) curve for the cup prominence logistic regression model. Reprinted with permission from the British Editorial Society of Bone & Joint Surgery

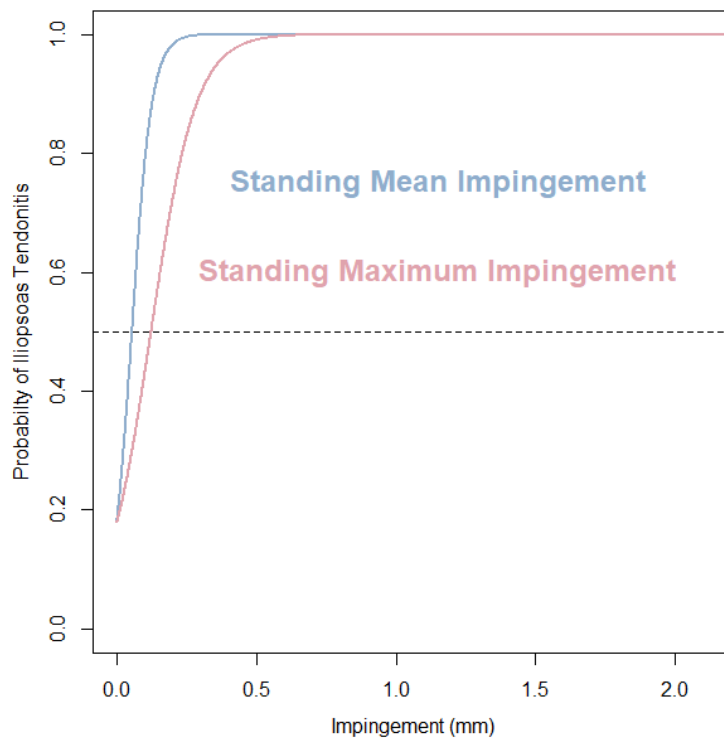


Figure 25 Logistic regression models for standing mean and maximum impingement to predict groin pain. Both significantly predicted the probability of iliopsoas tendinitis ($p < 0.05$). Reprinted with permission from the British Editorial Society of Bone & Joint Surgery.

Table 6 Logistic regression model for predicting the probability of iliopsoas tendonitis with standing mean impingement.

Parameter	Standard Error	Coefficient	p-value
(intercept)	0.50	-1.50	< 0.01
Standing Mean Impingement	11.90	27.94	0.01

Table 7 Logistic regression model for predicting the probability of iliopsoas tendonitis with standing maximum impingement.

Parameter	Standard Error	Coefficient	p-value
(intercept)	0.51	-1.52	< 0.01
Standing Max Impingement	5.26	12.42	0.01

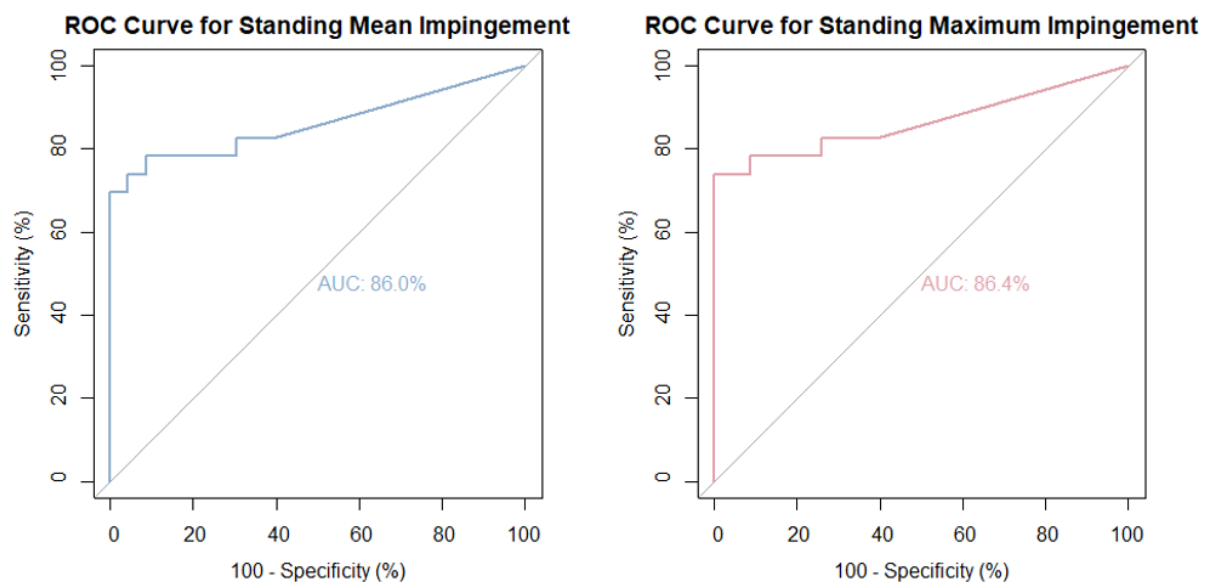


Figure 26 Receiver operating characteristic (ROC) curves for the standing mean impingement and standing maximum impingement logistic regression models. Reprinted with permission from the British Editorial Society of Bone & Joint Surgery.

Discussion

A novel simulation was developed that can detect symptomatic iliopsoas tendonitis via a retrospective, case-controlled investigation with the symptomatic patients exhibiting significantly greater levels of simulated impingement. Impingement measured by the simulation was a stronger predictor of iliopsoas tendonitis than the conventional cup prominence measurement.

Similar levels of cup prominence were found in the symptomatic cohort to previous investigations into patients with iliopsoas tendonitis.^{143,147,162,165} However, as illustrated through the logistic regression models, cup prominence did not predict iliopsoas tendonitis as well as the simulation. This may be due to inaccuracies associated with taking measurements on 2D slices from CT studies to investigate 3D structures.^{166,167} For example, despite several patients in the asymptomatic cohort having relatively high cup prominence values, no impingement between the iliopsoas and cup was observed in these patients. This indicated that the simulation could differentiate between cup prominence that results in impingement and cup prominence that does not. These findings are likely due to these patients' combined pelvic and femoral kinematics preventing the iliopsoas from impinging with the acetabular cup. If this belief is correct, it would shed light on the kinematic relevance of spino-pelvic and pelvic-femoral motion to iliopsoas irritation, concepts that are explored in a later chapter of this dissertation (*Chapter 5: Determination of preoperative risk factors for iliopsoas tendonitis after total hip arthroplasty*).

Interestingly, three symptomatic patients had no impingement detected by the simulation ('false negatives') but relatively high cup prominence values and very large diameter femoral heads (>40mm) with monoblock cups. In these cases, the femoral head was preventing the iliopsoas and cup from impinging by 'lifting' the iliopsoas off the exposed cup. Despite no impingement between the iliopsoas and cup, these patients were still diagnosed with iliopsoas tendonitis and there may be multiple other reasons for their diagnosis. First, large diameter femoral heads may irritate the iliopsoas by 'stretching' it.^{129,138,139} Second, a high combined functional anteversion may lead the iliopsoas to function as an 'anterior stabiliser' to the prosthetic joint, causing overuse and irritation,^{128,157,158} or leading to posterior prosthetic impingement that irritates the iliopsoas through repeated anterior micro-instability. Third, there may have been excessive lengthening or offset changes made intraoperatively.¹²⁵ The existence of these patients led to the baseline risk of approximately 18% chance of iliopsoas tendonitis after THA, despite zero impingement. This reflects the multi-causal nature of postoperative groin pain, which may be caused by reasons other than impingement with the cup.^{125,128,129,133,134,138,139,143,154} Similarly, four asymptomatic patients had very little impingement (<0.15mm) detected by the simulation ('false positives'), which may indicate a threshold level of impingement for irritation to occur or may represent the margin of error of the simulation.

This study had several limitations. First, the retrospective nature of the study meant that not all patients had the requisite imaging, necessitating exclusion from the study. The retrospective nature of the study also presented limitations regarding the lack of preoperative data. After removal of the native femoral head and insertion of the femoral and acetabular components from THA surgery, the pathway traced by the iliopsoas will change, and the extent of this change may also be a contributing factor to the onset of tendonitis. For example, it is known that excessive lengthening at the hip or changes to offset can irritate the iliopsoas,¹²⁵ however, there may be other pre- to postoperative changes that also irritate the iliopsoas, such as changes in functional femoral rotation. The availability of preoperative CT scans would have allowed for simulation of the preoperative iliopsoas and comparison to the postoperative iliopsoas, which might have given insight into the other sources of tendonitis. Second, sample size-related limitations are likely the reason for not observing a statistically significant difference in cup anteversion or cup size, as these have been shown to be a risk factor for iliopsoas impingement.¹⁶³ Third, although treatment and management was reported for the symptomatic patients, the outcomes of these treatments were not reported. Approaches to treating iliopsoas tendonitis are well documented in previous literature and this was not an objective of the study. However, an investigation of the relationship between the level of impingement and the success of different treatments paths may be warranted. Finally, changes in functional femoral rotation from supine to standing, which has been shown to have significant variation, were not addressed.^{22,23}

Further research may involve investigating the impingement values in cohorts of symptomatic and asymptomatic patients with hip resurfacing arthroplasties. This may provide insight into differing mechanisms of groin pain as these two operations have been reported to have significantly different incidences of groin pain.^{125,126,129,130,133,134} However, ultimately, the ambition for this simulation is to assist with preoperative planning for THAs by guiding decisions about optimal cup placement in concert with other tools, such as prosthetic and bony impingement simulations.

In conclusion, a novel computational model that can quantify impingement has been developed and its accuracy has been verified through a case-controlled investigation by simulating impingement in symptomatic and asymptomatic patients. However, iliopsoas tendonitis is a complex issue and not simply related to acetabular cup exposure. This tool has the potential to be used preoperatively, to guide decisions about optimal cup placement, and postoperatively, to aid in the diagnosis of iliopsoas tendonitis and determine an appropriate treatment pathway.

CHAPTER 3: COMPARISON OF ILIOPSOAS TENDONITIS AFTER HIP RESURFACING ARTHROPLASTY AND TOTAL HIP ARTHROPLASTY: A CASE-CONTROLLED INVESTIGATION USING A VALIDATED SIMULATION

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Abstract

INTRODUCTION: Iliopsoas tendonitis occurs in up to 30% of patients after hip resurfacing arthroplasty (HRA) and is a common reason for revision. Most studies into iliopsoas tendonitis after hip arthroplasty investigate its incidence or the success of different treatment paths. Only one previous study has attempted to simulate iliopsoas impingement pre- or postoperatively in patients who have undergone THA and been diagnosed with iliopsoas tendonitis, and none have assessed this in a sample of patients who have undergone HRA. However, the incidence of groin pain after HRA is meaningfully higher than THA and theories have been proposed for causes of groin pain that are independent of impingement with the acetabular cup. Therefore, the aims of this study were to examine the nature of iliopsoas tendonitis to understand if its mechanism differs between HRA and THA patients using a case-controlled investigation designed similarly Chapter 2.

METHOD: A retrospective search was conducted in an experienced surgeon's database for HRA patients with iliopsoas tendonitis, resulting in two cohorts of 12 patients. Inclusion criteria included a postoperative CT scan, standing x-ray, and patients having exceeded 6 months from surgery. Using the CT scans, 3D models of the femur and pelvis were segmented and landmarked, and the femoral and acetabular components were registered to their implanted positions. These 3D models were used to simulate the iliopsoas impingement in both supine and standing pelvic positions. Three discrete impingement values were recorded for each patient in supine and standing, and the mean and maximum of these values were reported. Cup prominence was measured using a previously described method of taking the greatest point of anterior prominence in axial slices of a CT scan. Receiver operating characteristic (ROC) curves were generated to determine the model's sensitivity, specificity, and area under the curve (AUC).

RESULTS: The mean cup prominence for the symptomatic cohort was 10.7mm and 5.1mm for the asymptomatic cohort ($p < 0.01$). Regarding assessment of the simulation's accuracy in HRA patients, impingement significantly predicted the probability of iliopsoas tendonitis in logistic regression models with a sensitivity of 83%, specificity of 100%, and an AUC ROC curve of 0.95. Unexpectedly, the HRA cohort exhibited less impingement than the THA cohort.

CONCLUSIONS: In separate case-controlled investigations, this novel simulation's accuracy in detecting iliopsoas impingement and differentiating between the symptomatic and asymptomatic cohorts has now been assessed in investigations of THA and HRA patients. Interestingly, in this study, the HRA patients demonstrated less impingement than the symptomatic THA patients, despite greater cup prominence. This may indicate that the mere presence of impingement between the iliopsoas and acetabular cup is a greater predictor of tendonitis manifesting than the magnitude of impingement. In conclusion, this tool has the potential to be used preoperatively, to guide decisions about optimal cup placement, and postoperatively, to assist in the diagnosis of iliopsoas tendonitis.

Introduction

Hip Resurfacing Arthroplasty (HRA) is an alternative surgical treatment to total hip arthroplasty (THA) for end-stage osteoarthritis (OA) of the hip. When indicated for the appropriate patient, HRA demonstrates equivalent rates of revision to THA^{168,169} whilst also preserving more bone stock^{170,171} and better restoring native biomechanics than THA.⁵¹ However, groin pain, specifically iliopsoas tendonitis,^{129,133,134} remains a common complication after HRA.

Iliopsoas tendonitis may have several causes, but it is most frequently attributed to impingement of the anterior edge of the acetabular cup with the iliopsoas tendon. This can occur due to lateralisation, under-anteversion, or oversizing of the acetabular implant.^{126,127,136} Iliopsoas tendonitis has also been attributed to large diameter femoral heads,^{129,133,134,138,172} particularly in HRA. In HRA the native femoral head and neck dimensions largely dictate the size of the implanted components. This generally results in larger cup sizes in HRA than in THA¹⁷³ where the implanted cup size and head size is dependent upon the acetabular bone. For example, femoral head sizes in THA implant systems typically range from 28mm to 36mm, whereas HRA femoral head sizes typically range from 46mm to 58mm. Another difference between HRA and THA is the material: HRAs are typically metal-on-metal (MoM), whereas most modern THA bearing surfaces are some combination of polymer and ceramic. Metal debris is known to cause inflammation, necrosis of tissue, and pain^{79,86} and therefore may present as postoperative groin pain. Consequently, it could be posited that all the major sources of iliopsoas tendonitis mentioned above would be more common in HRA than in THA.

Most studies into iliopsoas tendonitis after hip arthroplasty investigate its incidence^{125,126,129,130,132–134} or the success of different treatment paths^{135,143,162,174}, which include physical therapy, corticosteroid injections, iliopsoas tenotomy, and acetabular cup revision. Only one previous study has attempted to simulate iliopsoas impingement pre- or postoperatively in patients who have undergone THA and been diagnosed with iliopsoas tendonitis. No studies have done so in a sample of patients who have undergone HRA. However, with an incidence of between 18-30% for HRA, compared to 4-7% for THA, the incidence of groin pain after HRA is meaningfully higher^{125,126,128–131,133,134}, and theories have been proposed for causes of groin pain that are independent of impingement with the acetabular cup^{128,138,157,158}. Therefore, this study sought to examine the mechanism of iliopsoas tendonitis in HRA patients using a case-controlled investigation of symptomatic and asymptomatic patients, and compare these results to previously collected results of THA patients in a similarly designed study to understand if the mechanisms of cup impingement and tendonitis differ¹⁷⁵.

The hypotheses were two-fold. First, that the symptomatic cohort of HRA patients would demonstrate significantly greater levels of impingement than the asymptomatic HRA patients in

supine and standing positions. Second, the impingement in the symptomatic HRA cohort would exceed that of the previously studied THA cohort owing to the larger acetabular cups associated with HRA.

Patients and Methods

This was a retrospective, case-controlled investigation of symptomatic patients who were diagnosed with iliopsoas tendonitis after HRA surgery and patients who were not diagnosed with iliopsoas tendonitis after HRA surgery. Having previously assessed the simulation's accuracy in detecting iliopsoas impingement in a THA cohort using a case-controlled study design,¹⁷⁵ the same study design was pursued to assess the simulation in a HRA cohort. This comparison between experimental and control cohorts was undertaken as it demonstrates that the simulation can distinguish between symptomatic and asymptomatic patients. The primary outcomes of the study were the differences in impingement between the symptomatic and asymptomatic HRA cohorts, and the symptomatic THA and HRA cohorts. Secondary outcomes were differences in cup orientation, supine and standing pelvic tilt, cup prominence, or implant sizes between the symptomatic and asymptomatic HRA cohorts. Ethics was approved by the Bellberry Human Research Ethics Committee (study number 201203710).

Patient Selection

A retrospective search was conducted in an experienced surgeon's database for patients who underwent HRA surgery and were diagnosed with iliopsoas tendonitis. Diagnosis of iliopsoas tendonitis was confirmed via the active hip flexion test in supine. Diagnostic criteria included no pain at rest, no pain with passive flexion of 10°, and pain with active flexion of 10° with a straight leg raise. The same tests were performed in seated without passive flexion as a secondary confirmation. Inclusion criteria were patients who had undergone HRA, had received a postoperative computed tomography (CT) scan, and a standing x-ray with minimum 6 months' follow-up. Exclusion criterion was elevated metal ion levels. After application of the inclusion and exclusion criteria, 12 symptomatic patients remained. The asymptomatic cohort was established by randomly selecting 12 patients from the same surgeon's database who had undergone HRA surgery but had not been diagnosed with iliopsoas tendonitis and who met the inclusion and exclusion criteria. Details of the patient cohorts can be found in Table 8 and the patient select flow chart can be seen in Figure 27.

An overview of the study methods involved in simulating iliopsoas impingement can be found below; however, a more detailed description can be found in the previous chapter, which is based off a study by Hardwick-Morris et al.¹⁷⁵

Table 8 Deidentified details of the symptomatic and asymptomatic HRA patient cohorts, including age at surgery, gender, implant sizes, surgical approach, and the treatment the patient underwent.

Patient ID	Age	Gender	Side	Cup Size	Head Size	Cohort	Surgical Approach	Treatment for Iliopsoas Tendonitis
1	52	M	Right	54	48	Symptomatic	Posterior	Revision to THA
2	55	M	Left	56	50	Symptomatic	Posterior	Iliopsoas injection followed by arthroscopic release
3	33	M	Left	56	50	Symptomatic	Posterior	Iliopsoas injection
4	66	M	Left	60	54	Symptomatic	Posterior	Acetabular cup revision
5	54	M	Left	56	50	Symptomatic	Posterior	Iliopsoas injection
6	65	M	Left	56	50	Symptomatic	Posterior	Arthroscopic iliopsoas release followed by open iliopsoas release and capsulotomy
7	49	M	Right	58	52	Symptomatic	Posterior	Conservative treatment – exercise modification
8	51	M	Right	60	54	Symptomatic	Posterior	Iliopsoas injection followed by arthroscopic iliopsoas release
9	72	M	Right	62	56	Symptomatic	Posterior	Iliopsoas injection followed by arthroscopic iliopsoas release
10	54	M	Right	58	52	Symptomatic	Posterior	Iliopsoas injection
11	62	M	Right	60	54	Symptomatic	Posterior	Arthroscopic iliopsoas release
12	55	M	Right	60	54	Symptomatic	Posterior	No treatment
13	48	M	Left	58	52	Asymptomatic	Posterior	n/a
14	62	M	Right	62	56	Asymptomatic	Posterior	n/a
15	60	M	Right	58	51	Asymptomatic	Posterior	n/a
16	52	M	Left	56	50	Asymptomatic	Posterior	n/a
17	52	M	Right	56	50	Asymptomatic	Posterior	n/a
18	74	M	Left	58	52	Asymptomatic	Posterior	n/a
19	51	M	Left	58	52	Asymptomatic	Posterior	n/a
20	70	M	Left	58	52	Asymptomatic	Posterior	n/a
21	70	M	Left	60	54	Asymptomatic	Posterior	n/a
22	65	M	Right	58	52	Asymptomatic	Posterior	n/a
23	64	M	Left	60	54	Asymptomatic	Posterior	n/a
24	61	M	Left	58	52	Asymptomatic	Posterior	n/a

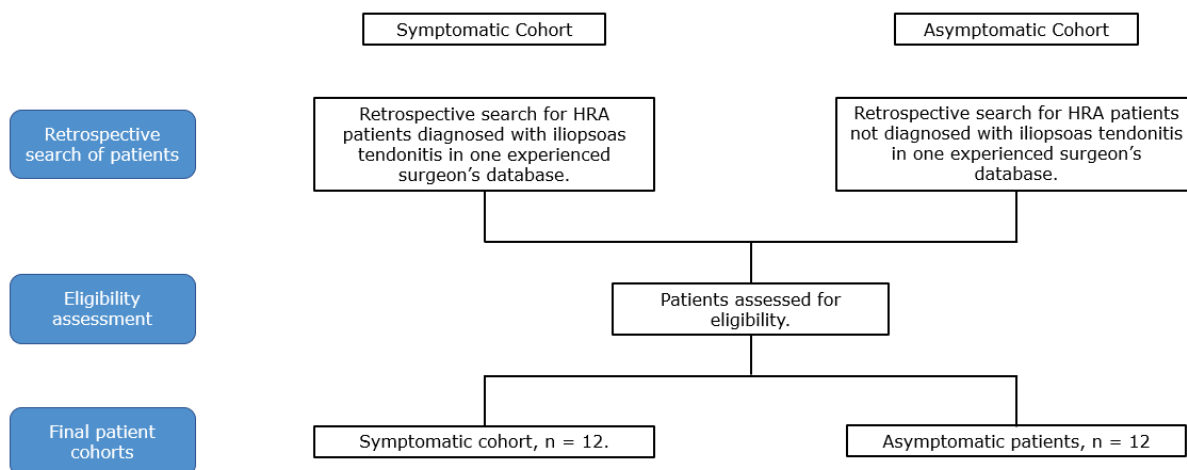


Figure 27 Flow chart of the patient selection process for the symptomatic cohort, which includes patients who were diagnosed with iliopsoas tendonitis, and asymptomatic cohort, which includes patients that were not diagnosed with iliopsoas tendonitis. The final cohorts contained 12 patients each. Reprinted with permission from John Wiley & Sons, Inc.

Simulation of Iliopsoas Impingement

3D models of each patient's pelvis and operative femur were generated by segmenting the CT scans in ScanIP R-2020.09 (Synopsis, California, USA) using a combination of manual segmentation, augmented with in-built functions. The iliopsoas insertion points, anterior pelvic plane (APP) landmarks (left and right anterior superior iliac spine points and the pubic symphysis), and the femoral head centre were landmarked, and the hip resurfacing implants were registered to their in-situ positions in ScanIP.

Meshes of the bony anatomy and registered implants were imported into R Studio v1.3.1903 (Boston, MA, USA) in their supine (CT) positions and a representation of the iliopsoas was generated using a novel approach to tracing the path from each superior insertion point of the iliopsoas to the inferior insertion point at the lesser trochanter (LT). The three superior insertion points of the iliopsoas included one point on the lateral superior plateau of the patient's L5 vertebrae, the lateral-most point on the patient's L5 transverse process, and a point 3 to 5mm lateral of the patient's sacroiliac joint. These points were observed to be reproducible landmarks that provided an accurate representation of the width of the iliopsoas and the location the it passes over the acetabular margin of the pelvis. Landmarks on L5 were chosen as this vertebra was present in all CT scans.

Each combination of superior and inferior insertion sites creates a segment, and each segment is comprised of two paths: a green path and a red path. The green and red paths wrap around the pelvis, prosthetic femoral head, and operative femur. However, the green path does not include the acetabular cup in its wrapping path and the red path does. Therefore, impingement is quantified as the difference of these two path lengths, which could also be considered the 'stretch' of the

iliopsoas due to the acetabular cup (Figure 28). In cases with no iliopsoas impingement, the green and red path lengths are of equal length and in cases with iliopsoas impingement, the red path is longer than the green path. Three separate impingement values (one for each segment) are calculated and reported as the mean and maximum of these values. The pelvis is then rotated to the patient's standing pelvic position using the difference in sagittal pelvic tilt between supine and standing, and the same impingement detection algorithm was applied. Therefore, there are four iliopsoas impingement measurements for each patient: supine mean impingement, supine maximum impingement, standing mean impingement, and standing maximum impingement.

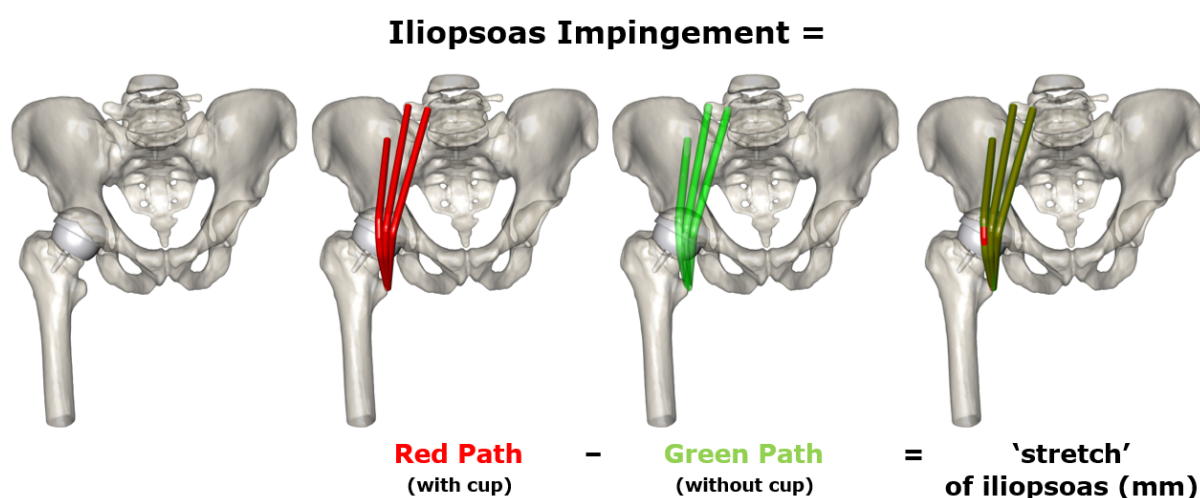


Figure 28 Schematic of the iliopsoas impingement simulation. Three segments represent the approximate the width of the iliopsoas and the location it passes over the acetabular margin. The green and red paths wrap around the pelvis, prosthetic femoral head, and operative femur. However, the green path does not include the acetabular cup in its wrapping path and the red path does. Therefore, impingement is quantified as the difference of these two path lengths, which could also be considered the 'stretch' of the iliopsoas due to the acetabular cup. Reprinted with permission from John Wiley & Sons, Inc.

Cup prominence was also measured using the method proposed by Cyteval et al.¹⁴⁷ to compare to the iliopsoas impingement simulation's predictive power.

Statistical Analysis

Statistical analysis was performed in R Studio. An α value of 0.05 was used to determine clinical significance. Shapiro-Wilk tests were performed to determine whether measurements were normally distributed or not. For normally distributed data, two-way, independent-samples t-tests were used to determine significant difference for continuous variables. For data that was not normally distributed, Mann-Whitney U tests were used to determine significant difference between continuous variables. For categorical variables, Chi-Squared tests were used to determine significant difference. Logistic regression models were used to test if cup prominence, standing mean impingement, standing maximum impingement values predicted the probability of iliopsoas tendonitis. Receiver operator characteristic (ROC) curves were generated to determine the

simulation's area under the curve (AUC) and optimal predictive threshold for sensitivity and specificity.

Results

No statistically significant difference between symptomatic and asymptomatic cohorts was found for cup anteversion, cup inclination, cup size, femoral head size, supine pelvic tilt, or standing pelvic tilt (Table 9). The mean cup prominence for the symptomatic cohort was 7.6mm ($\pm$ 3.0mm) and 3.7mm ($\pm$ 2.7mm) for the asymptomatic cohort. The difference was statistically significant (p = 0.003) (Figure 29).

Table 9 Implant, patient, cup prominence, and iliopsoas impingement results for both cohorts of HRA patients. n.s = not significant, † = Student's T-Test, ‡ = Chi-Squared Test.

Parameter	Cohort	Mean	Range	Standard Deviation	p-Value
APP Inclination	Symptomatic	35.8	19.5 – 42.7	6.1	n.s†
	Asymptomatic	39.1	16.2 – 48.3	8.0	
APP Anteversion	Symptomatic	11.4	0.4 – 25.8	9.5	n.s†
	Asymptomatic	17.3	4.1 – 41.8	12.1	
Supine Pelvic Tilt	Symptomatic	3.0	-4.3 – 11.3	4.7	n.s†
	Asymptomatic	2.2	-6.6 – 11.4	5.1	
Standing Pelvic Tilt	Symptomatic	-3.2	-11.3 – 13.6	6.5	n.s†
	Asymptomatic	-1.0	-14.6 – 7.1	6.2	
Head Size	Symptomatic	52.0	48 – 56	2.4	n.s‡
	Asymptomatic	52.3	50 – 56	1.7	
Cup Size	Symptomatic	58.0	54 – 62	2.4	n.s‡
	Asymptomatic	58.3	56 – 62	1.7	
Cup Prominence	Symptomatic	7.6	0 – 11.1	3.0	0.003†
	Asymptomatic	3.7	0 – 7.9	2.7	
Supine Mean Impingement	Symptomatic	0.10	0.0 – 0.30	0.10	0.007†
	Asymptomatic	0.00	0.0 – 0.04	0.01	
Standing Mean Impingement	Symptomatic	0.11	0.0 – 0.38	0.12	0.008†
	Asymptomatic	0.00	0.0 – 0.03	0.00	
Supine Maximum Impingement	Symptomatic	0.21	0.0 – 0.70	0.21	0.006†
	Asymptomatic	0.01	0.0 – 0.07	0.02	
Standing Maximum Impingement	Symptomatic	0.24	0.0 – 0.77	0.25	0.007†
	Asymptomatic	0.00	0.0 – 0.04	0.01	

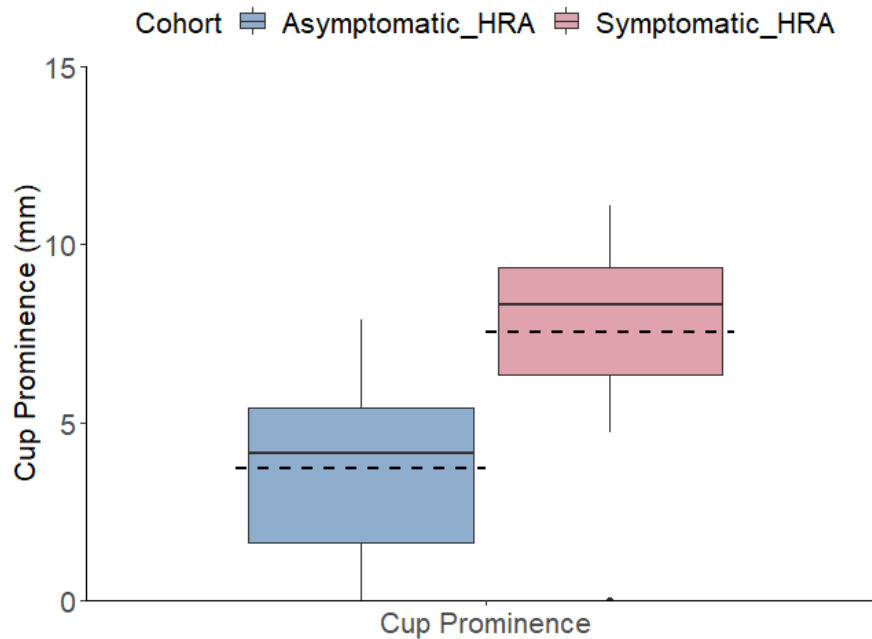


Figure 29 Cup prominence results for the symptomatic and asymptomatic cohorts. The symptomatic cohort had significantly greater cup prominence values. The edges of the box represent the 25th and 75th percentiles, the solid line within the box represents the median, the dashed line represents the mean, the lines represent the ranges, and the dots represent the outliers. Reprinted with permission from John Wiley & Sons, Inc.

The average supine mean impingement for the symptomatic cohort was 0.10mm ($\pm$ 0.10mm) and 0.00mm ($\pm$ 0.01mm) for the asymptomatic cohort. The difference was statistically significant ($p = 0.007$). The average standing mean impingement for the symptomatic cohort was 0.11mm ($\pm$ 0.12mm) and 0.0mm ($\pm$ 0.00mm) for the asymptomatic cohort. The difference was statistically significant ($p = 0.008$). The average supine maximum impingement for the symptomatic cohort was 0.21mm ($\pm$ 0.21mm) and 0.01mm ($\pm$ 0.02mm) for the asymptomatic cohort. The difference was statistically significant ($p = 0.006$). The average standing maximum impingement for the symptomatic cohort was 0.24mm ($\pm$ 0.25mm) and 0.00mm ($\pm$ 0.01mm) for the asymptomatic cohort. The difference was statistically significant ($p = 0.007$) (Figure 30). A post-hoc power calculation determined that these results had 91.4% power with an alpha of 0.05.

The results of the symptomatic cohort from the previous validation study of THA patients were as follows: average supine mean impingement was 0.3mm ($\pm$ 0.4mm), average standing mean impingement was 0.4mm ($\pm$ 0.5mm), average supine maximum impingement was 0.7mm ($\pm$ 0.8mm), average standing maximum impingement for the symptomatic cohort was 0.7mm ($\pm$ 0.9mm). These were all significantly greater than the symptomatic HRA cohort and can be seen in Figure 30.

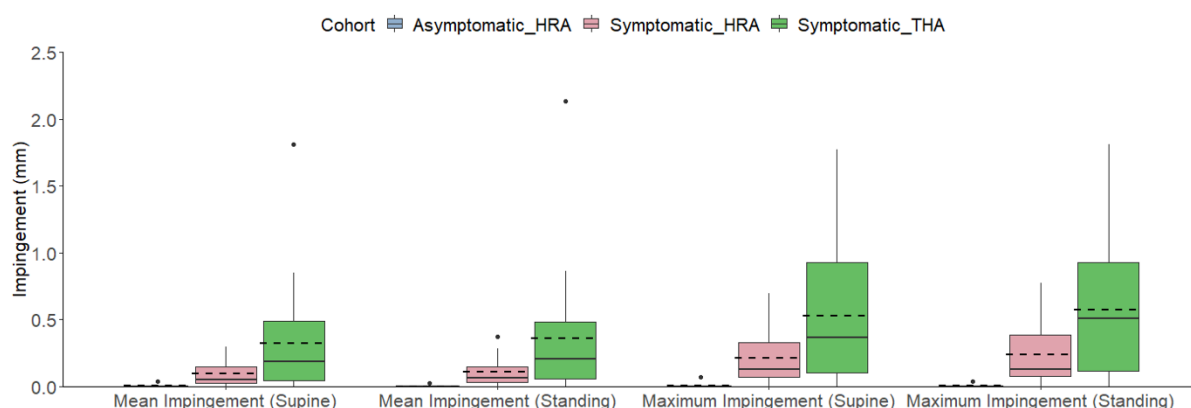


Figure 30 Mean and maximum impingement results for the symptomatic HRA, asymptomatic HRA, and symptomatic THA cohorts in supine and standing positions. As hypothesised, the symptomatic HRA cohort had significantly greater mean and maximum impingement values in both standing and supine than the asymptomatic HRA cohort. Contradicting our second hypothesis, the symptomatic THA cohort had significantly greater mean and maximum impingement values in both standing and supine than the symptomatic HRA cohort. Reprinted with permission from John Wiley & Sons, Inc.

Cup prominence significantly predicted the probability of iliopsoas tendonitis in a logistic regression model ($p = 0.02$) (Table 10). The optimal cut-off point for cup prominence as a predictor of iliopsoas tendonitis was 5.7mm. Using this cut-off point, the logistic regression model showed a sensitivity of 83%, specificity of 83%, and an AUC of 0.85 (Figure 31). Standing mean impingement ($p = 0.03$) and standing maximum impingement ($p = 0.03$) significantly predicted the probability of iliopsoas tendonitis in logistic regression models (Table 11 and Table 12). The optimal cut-off point for maximum impingement as a predictor of iliopsoas tendonitis was 0.05mm. Using this cut-off point, the logistic regression model showed a sensitivity of 83%, specificity of 100%, and an AUC of 0.95 (Figure 31).

Table 10 Logistic regression model for predicting the probability of iliopsoas tendonitis with cup prominence.

Parameter	Standard Error	Coefficient	p-value
(intercept)	1.24	-2.63	0.03
Cup Prominence	0.19	0.46	0.02

Table 11 Logistic regression model for predicting the probability of iliopsoas tendonitis with cup prominence.

Parameter	Standard Error	Coefficient	p-value
(intercept)	0.77	-1.75	0.02
Standing Mean Impingement	2.19	97.02	0.03

Table 12 Logistic regression model for predicting the probability of iliopsoas tendonitis with standing maximum impingement

Parameter	Standard Error	Coefficient	p-value
(intercept)	0.80	-1.88	0.02
Standing Maximum Impingement	24.29	51.86	0.03

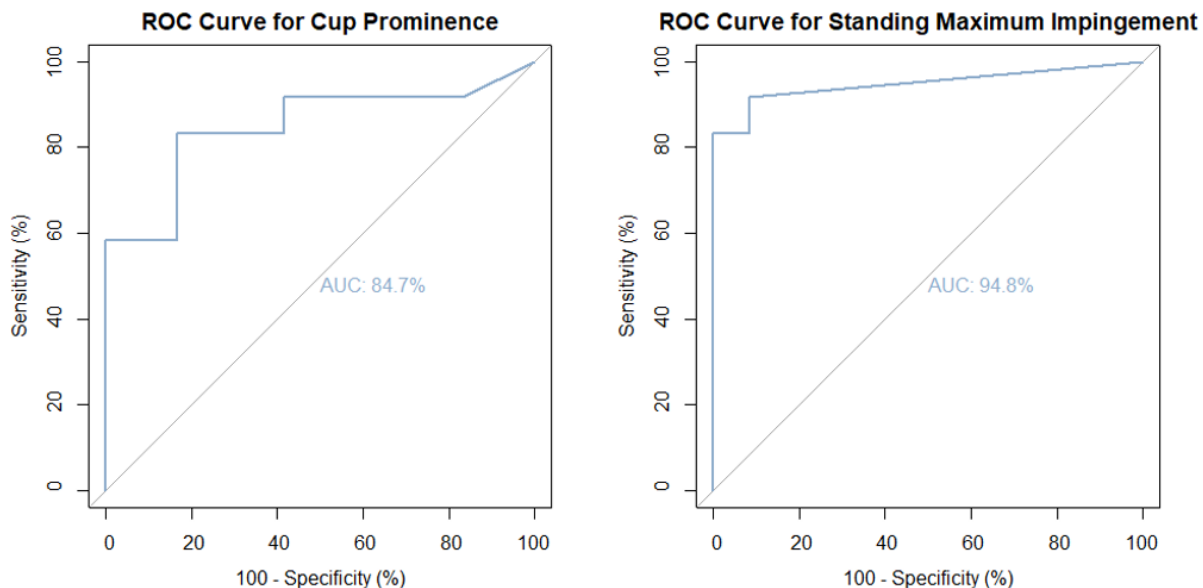


Figure 31 Receiver operating characteristic (ROC) curves for the cup prominence and standing maximum impingement logistic regression models. Reprinted with permission from John Wiley & Sons, Inc.

Discussion

The accuracy of this dissertation's novel iliopsoas impingement detection simulation has now been assessed in studies of HRA and THA patients by demonstrating that it can distinguish between patients who were symptomatic of iliopsoas tendonitis and patients who were not. As hypothesised, the symptomatic HRA cohort had significantly greater impingement than the asymptomatic HRA cohort. Using the optimal cut-off of maximum impingement, the simulation was also found to significantly predict the probability of iliopsoas tendonitis with a sensitivity of 83% and specificity of 100%.

Compared to the previous study of THA patients,¹⁷⁵ the simulation demonstrated improved sensitivity and specificity in the HRA cohort, despite lower overall impingement. This contradicted the study's second hypothesis that more impingement would be observed in the HRA patients due to the tendency to implant larger cups in HRA patients to accommodate the unresected femoral head. This finding of greater impingement in the symptomatic THA cohort may be a result of a sampling bias. However, if it is not, it could be explained by the larger prosthetic femoral head

elevating the iliopsoas off the edge of the acetabular cup, reducing the contact between the iliopsoas and acetabular cup, but also increasing the length of its wrapping path. This would provide further evidence of iliopsoas tendonitis and impingement being three-dimensional problems, not merely related to prominence of the cup when measured on a 2D axial slice of a CT scan.

These hypotheses attempt to explain why the incidence of iliopsoas tendonitis is greater after HRA surgery than THA surgery. However, this may not necessarily be the case as a study by Lavigne et al.¹³³ found the rates to converge over time and a study by Nam et al.¹³² found no difference in incidence. Therefore, further study into the incidence of iliopsoas tendonitis after both types of hip arthroplasty with detailed accounts of the location and severity of pain, while controlling for risk factors like age and gender, is warranted. It should be noted that it is not clear yet from either study if the amount of impingement observed in the simulation is reflective of the degree of irritation or pain experienced by the patient, or whether the mere presence of impingement with the sharp edge of the acetabular cup results in tendonitis.

Interestingly, there were two symptomatic patients for whom no impingement was observed; what will be referred to as a 'false negative'. These patients help illustrate the multicausal nature of iliopsoas tendonitis as the irritation in these patients was likely due to a cause other than impingement between the iliopsoas and acetabular cup, such as a large diameter femoral head. In fact, additional analysis was performed on one of these 'false negative' patients due to the availability of a preoperative CT scan. After segmenting the CT scan in ScanIP to reconstruct the preoperative bony anatomy, a representation of the iliopsoas was simulated using the same novel approach in the impingement detection simulation. However, instead of measuring the difference in path lengths for each of the three segments, only the length of each segment was reported. This analysis revealed that the iliopsoas had been lengthened by about 5mm from preoperative to postoperative states. It is possible that this effective lengthening through anteriorisation of the prosthetic femoral head may have been eliciting pain and irritation, despite a well-restored centre of rotation when viewed coronally. Similar ideas have been explored by Cobb et al.¹³⁸ in a study of virtual HRA surgery. This study posited that 'unexplained' postoperative pain may be caused by the metal prosthetic head extending beyond the limit of the native femoral head and functioning as a fulcrum to the iliopsoas in full extension.

An interesting hypothesis that follows on from our observations of 'false negative' patients who experience tendonitis from causes other than cup impingement and THA patients having greater iliopsoas impingement despite smaller acetabular cups is that the incidence of iliopsoas tendonitis is approximately equal between HRA and THA cohorts, but there is a sampling bias. In other words, the patients who receive HRA are generally younger and more active,^{134,176} and therefore more likely to partake in activities that irritate their iliopsoas via one of the studied causes of

iliopsoas tendonitis. Support for this hypothesis can be found in a study by Nam et al.¹³² who studied postoperative pain in young, active patients after THA and HRA and found no difference in the incidence of postoperative groin pain, which could be considered a proxy for iliopsoas tendonitis. Additionally, as previously mentioned, Lavigne et al.¹³³ observed that the rate of groin pain after HRA and THA may converge over time, with higher rates of groin pain in HRA patients at three months after surgery being plausibly due to soft tissue dissection in surgery and the larger native femoral necks pressing against the capsule while it is healing.

Yet to be explored is whether a relationship exists between postural factors, such as sagittal spinal alignment, pelvic tilt, and femoral rotation with iliopsoas tendonitis. The samples of symptomatic patients in our two studies are not large enough to draw any conclusions; however, both show trends of iliopsoas impingement increasing with posterior pelvic tilt, which could be explained by posterior tilt 'opening up' and exposing the wrapping path of the iliopsoas to more of the acetabular cup. Posterior pelvic tilt would also form a more acute wrapping angle of the iliopsoas around the acetabular margin, in addition to lengthening it, which may also elicit or worsen irritation.

A recent study by Okamoto et al.¹⁷⁷ that investigated the association between the psoas muscle index and sagittal spinal alignment with patient reported outcomes observed that flatback deformity and the psoas muscle index are predictors of whether a patient perceived their hip to be 'artificial' or not. It is unclear whether the psoas muscle index and flatback deformity exist in a causal relationship and, if so, what direction this causality occurs – whether flatback deformity leads to a reduction in psoas muscle mass or vice versa – however it does establish a link between postural factors, iliopsoas-related pathology, and hip arthroplasty surgery that warrants further exploration. With the introduction of ceramic-on-ceramic (CoC) HRA^{141,178} and anatomically contoured implant designs,¹⁴¹ it will also be interesting to study if the incidence of iliopsoas tendonitis after HRA is the same between CoC and MoM bearing surfaces due to the known irritation on soft tissue structures resulting from metal wear.

As far as the authors are aware, no previous studies have measured cup prominence in patients who have undergone HRA surgery and been diagnosed with iliopsoas tendonitis. Our results therefore provide insight into the level of anterior cup exposure observed in HRA patients who have been diagnosed with iliopsoas tendonitis. While the method described by Cyteval et al.¹⁴⁷ for measuring cup prominence on CT, or similar,¹⁶⁵ remains the conventional approach, our iliopsoas impingement detection simulation has demonstrated improved accuracy in studies of HRA and THA¹⁷⁵ patients. Having assessed the accuracy of this simulation in postoperative patient cohorts, future research may be undertaken in the preoperative context to determine risk factors that exacerbate iliopsoas tendonitis. However, the primary goal for this simulation is for it to be used as part of a three-dimensional preoperative templating workflow to assist in optimising cup orientation and positioning. Additionally, this novel approach to modelling muscles and tendons could be

extended to other soft tissue constructs around the hip joint, such as the abductors and capsular ligaments, to determine appropriate tensioning in the joint.

The findings of our study should be interpreted within the context of its limitations. First, this was a retrospective study, which meant that some patients required exclusion due to insufficient imaging. Second, sample size-related limitations may be the reason for not observing a statistically significant difference in cup anteversion or cup size, as these have been shown to be a risk factor for iliopsoas impingement.¹⁷⁹ Additionally, our cohorts contained only males, and extrapolation of our results to females may not be possible. However, this is reflective of the improved revision rates and outcomes of males with metal-on-metal HRA.^{168,176} Third, this study did not report on the outcomes of the symptomatic cohort. The success of various treatments and interventions for iliopsoas tendonitis have been studied in previous literature, and this was not an aim of the study. Fourth, this study did not address changes in functional femoral rotation from supine to standing, which has been shown to have significant variation, and this may increase or decrease the iliopsoas impingement.²³ Finally, due to limitations regarding preoperative data and imaging, our study did not address the changes in offset or length nor how these contributed to iliopsoas tendonitis. Regardless of the measurement approach, leg length measurements have been shown to have a high degree of variability¹⁸⁰ and dramatic changes to this from pre- to postoperative states may be a contributor to irritation of the iliopsoas. However, it should be noted that HRA is more limited than THA in its ability to correct for large leg length discrepancies, and we believe this would not have significantly impacted our results.

CHAPTER 4: FUNCTIONAL FEMORAL ANTEVERSION: AXIAL ROTATION OF THE FEMUR AND ITS IMPLICATIONS FOR COMPENSATORY MECHANISMS IN TOTAL HIP ARTHROPLASTY

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Abstract

INTRODUCTION: Acetabular and femoral component positioning are important considerations in reducing adverse outcomes after total hip arthroplasty (THA). Previous assessments of femoral anteversion examined anatomic femoral anteversion referenced to anatomic landmarks. However, this does not provide a functional understanding of the femur's relationship to the hip. We investigate a new measurement, functional femoral anteversion (FFA), and sought to measure its variability across a large sample of patients undergoing THA. Additionally, we investigated the possibility of compensatory mechanisms occurring at the hip joint to understand its implications for soft tissue disorders, such as iliopsoas tendonitis.

METHODS: 1008 consecutive patients underwent THA surgery between September 2019 and July 2021. Measurements were taken for all patients, including supine and standing Functional Femoral Rotation (FFR), Anatomic Femoral Anteversion (AFA), and Functional Femoral Anteversion (FFA).

RESULTS: The mean standing FFA was $13.2^{\circ} \pm 12.2^{\circ}$ (-27.8° to 52.3°). The mean change in FFR from supine to standing was $-2.2^{\circ} \pm 11.8^{\circ}$ (-43.0° to 41.9°). 161 (16%) patients had standing FFA version of greater than 25° . 460 (46%) of patients had standing FFR (internal or external) of greater than 10° . 123 (12%) patients exhibited an increase in external rotation from supine to standing of greater than 10° . A moderate, negative linear relationship was observed between AFA and standing external femoral rotation ($p < 0.001$, $R = -0.46$), indicating people may externally rotate their femur as AFA decreases with age.

CONCLUSIONS: Functional alignment of the femur in patients requiring THA is under-studied. It is now understood that the femur, like the pelvis, can rotate substantially between functional positions. Enhancing our understanding of FFA and FFR may improve both acetabular and femoral component positioning.

Introduction

Acetabular cup positioning has long been recognized as an important consideration in total hip arthroplasty (THA).^{57,181–185} Malpositioning of the acetabular cup has been shown to lead to increased rates of wear, edge loading, and impingement which may lead to instability, osteolysis, or dislocation.^{57,181–185}

Lewinnek et al. were among the first authors to recognize the relationship between acetabular cup positioning and dislocation rates by proposing a widely cited ‘safe zone’⁶⁹ that was believed to reduce the incidence of dislocation. However, further examination in larger samples of THA patients revealed that it does not preclude dislocation^{72,73} and is insufficient for surgical guidance.

Assessments of pelvic tilt in functional positions, when edge-loading and impingement are most likely,^{185,186} later revealed large inter-individual variability between positions^{74,75,96} with pelvic rotation between positions as low as 5° and as high as 70°. These changes in pelvic tilt would correspond to changes in acetabular anteversion of 4° and 50°, respectively,⁷⁶ and help explain why some individuals with a given cup orientation dislocate while others with the same cup orientation do not.

Like the variability of pelvic tilt, investigations into anatomic femoral anteversion (AFA) revealed large variability,^{17,18,20,187} with a range of up to 80°. ¹⁸ Gender and age differences were also observed, with AFA decreasing for males as age increases.¹⁸ These studies measured AFA as the angle between the femoral neck and the posterior condylar line (PCL) projected onto the axial plane^{17,20,187} or onto a plane perpendicular to the long femoral axis.¹⁸ This measurement references only anatomic landmarks and is constant between different patient positions as it does not account for functional femoral rotation (FFR). However, supine and standing FFR have been shown to vary significantly between individuals^{21,188} and change from pre- to post-surgery following THA.^{22,188} These rotational changes would alter the functional stem anteversion (FSA) of an implanted femoral component and thus have implications for the optimal femoral stem target. Specifically, individuals who exhibit high internal FFR may be at risk of anterior impingement when anatomic stem anteversion (ASA) is low or negative, and individuals who exhibit high external FFR may be at risk of posterior impingement when ASA is high.

In previous chapters, this dissertation identified that there may be an important relationship between the relative orientations of the pelvis and femur (pelvic-femoral kinematics) in the aetiology of iliopsoas tendonitis. Specifically, external FFR may provide protection against impingement between the iliopsoas and acetabular cup, and internal FFR may exacerbate it. Evidence for this was observed through the presence of asymptomatic patients in the case-controlled investigation of THA patients¹⁷⁵ who had relatively high cup prominence, yet no impingement between the iliopsoas and acetabular cup. It was believed that this was due to

favourable kinematics of the pelvis and femur protecting against this interaction. Therefore, the aims of this study were three-fold. First, to further investigate the variability of a new measurement proposed by Uemura et al.²² called functional femoral anteversion (FFA) across a larger sample of patients undergoing THA. Second, to assess its implications for femoral stem version targets and the number of individuals whose FFR would transition them out of suggested combined anteversion zones. Third, to investigate the presence of soft tissue compensatory mechanisms occurring at the hip joint that correct anatomic variation to maintain capsular tension, a phenomenon previously suggested by Akiyama et al.²⁴ in their study of femoral axial alignment. Specifically, if patients tend to externally rotate their femur as AFA decreases, it would provide evidence for a compensatory mechanism occurring at the hip joint to correct soft tissue laxity, and this would have implications for soft tissue disorders in patients that undergo large intraoperative changes to femoral anteversion.

Patients and Methods

1008 consecutive patients underwent THA surgery between September 2019 and July 2021. 627 were female (62%) and the average age was 66 (16 to 95). Inclusion criteria included patients that had a long limb CT scan and standing lateral X-ray of the distal femur (Figure 32) as part of the 360 Med Care (Sydney, Australia) THA preoperative planning protocol. The lateral knee radiograph taken was previously not standardised and, as far as the authors are aware, not routinely taken for any other preoperative THA planning protocol. However, the imaging protocol contains detailed instructions for radiographers to position the patient and acquire the imaging, and all radiology centres must be approved via an in-person explanation of the protocol. It was believed that these steps would ensure repeatable lateral knee radiographs of patients in standing and permit accurate measurement of their FFR. From this imaging data, assessments were made for supine and standing FFR, defined as the angle between the PCL and the coronal plane; and for AFA, defined as the angle between the femoral neck and the PCL, projected onto the femoral anatomic axis.

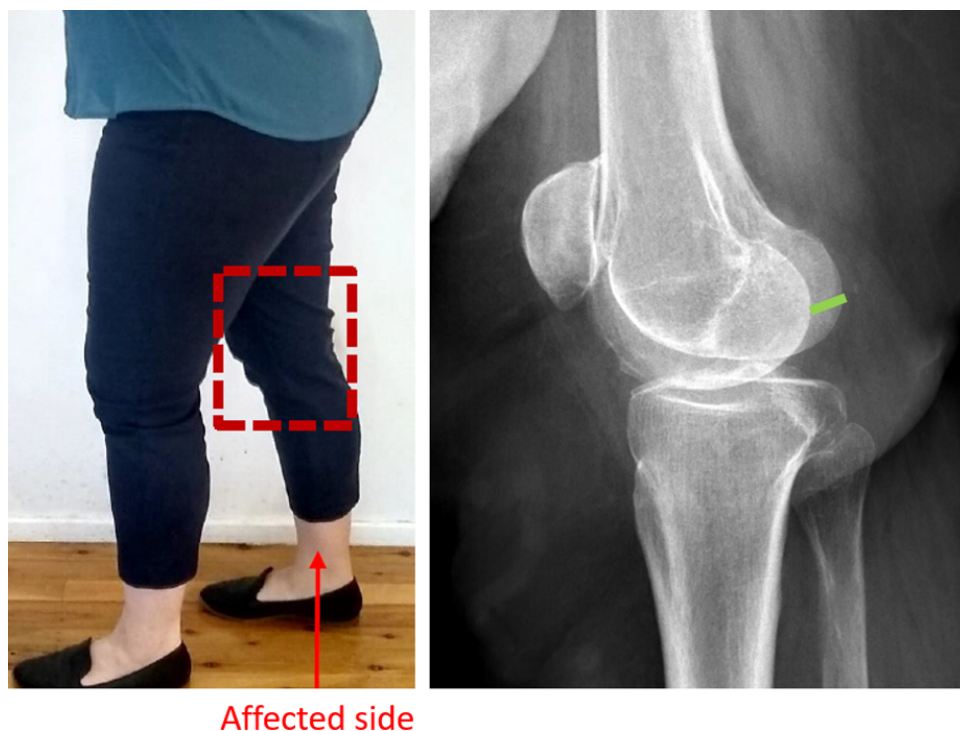


Figure 32 (Left) The stance taken by a patient while undergoing their preoperative functional knee radiology. (Right) Functional knee radiograph acquired preoperatively to enable calculation of the patient's standing Functional Femoral Rotation. Courtesy of Hardwick-Morris et al., *Arthroplasty Today*. Published by Elsevier. This work is licensed under a Creative Commons Attribution – Non-Commercial – No-Derivatives License (CC BY-NC-ND 4.0).

AFA was measured using the approach described by Pierrepont et al.¹⁸. The computed tomography (CT) scan was segmented in ScanIP Medical (Simpleware; Exeter, United Kingdom) to recreate 3D models of the patient's bony anatomy. Landmarks on the operative side were measured to establish the PCL and the femoral neck axis. Supine FFR was measured in RadiAnt DICOM Viewer v2.2.5.10715 (Medixant, Poland) on CT with a line that was tangential to the posterior femoral condyles and a horizontal baseline. Standing FFR was measured by first taking the sagittal distance between the posterior condyles on the lateral knee radiograph. A computational algorithm then recreated this distance in 3D using a segmented model of the patient's femur and modified the femoral rotation, measured against the coronal plane, until the length of the PCL converged to the value previously measured. This is equivalent to calculating the FFR required to make the PCL and coronal plane parallel. Positive FFR values were interpreted as external rotation. Therefore, adding the FFR to the AFA resulted in FFA. A visual representation of the relationship between AFA, FFR, and FFA can be found in Figure 33, which also shows the FSA by using 3D templating to recreate AFA.

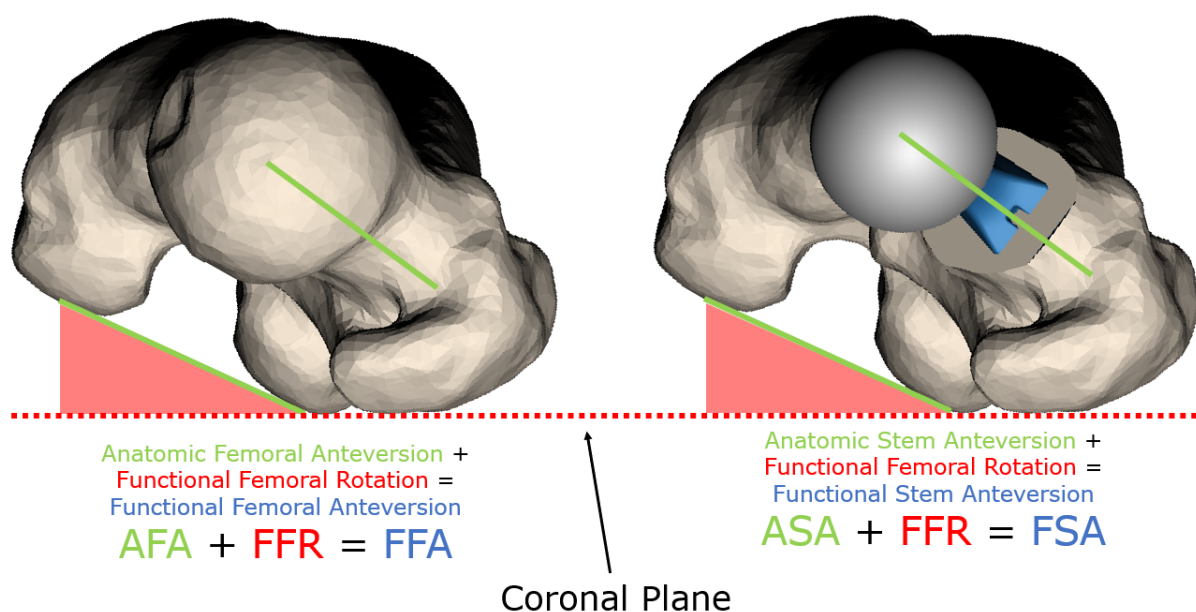


Figure 33 Left: Illustration of the relationship between Anatomic Femoral Anteversion, Functional Femoral Rotation, and Functional Femoral Anteversion. Right: Illustration of the relationship between Anatomic Stem Anteversion, Functional Femoral Rotation, and Functional Stem Anteversion using 3D templating to recreate the Anatomic Femoral Anteversion. Courtesy of Hardwick-Morris et al., Arthroplasty Today. Published by Elsevier. This work is licensed under a Creative Commons Attribution – Non-Commercial – No-Derivatives License (CC BY-NC-ND 4.0).

A positive change in FFA from supine-to-standing was interpreted as external rotation of the femur between these positions. All imaging and measurements were evaluated twice by qualified surgical planning engineers.

Statistical analysis

Statistical analysis was performed in R Studio v1.3.1903 (Boston, MA, USA). An alpha value of 0.05 was used to determine clinical significance. Two-way T-Tests were used to determine significant difference for continuous variables. Pearson's correlations were used to assess the linear relationship between continuous variables.

Ethics

This retrospective analysis was approved by the Bellberry Human Research Ethics Committee (study number 201203710).

Results

Results for the supine and standing FFR, AFA, standing FFA, and the change in FFA from supine to standing can be seen in Table 13. The mean supine FFR was $0.4 \pm 10.6^\circ$ (-34.0° to 31.4°). There was a significant gender difference ($p < 0.001$) with a mean female supine FFR of 3.3° (-31.4° to 31.4°) and -4.5° (-34.0° to 24.5°) for males. The mean AFA was $15.6^\circ \pm 9.8^\circ$ (-24.4° to 68.4°) and significant gender differences were observed ($p < 0.001$) (Figure 34). The mean female AFA was 16.8° (-24.4° to 63.6°) and 13.8° (-9.4° to 68.4°) for males. The mean standing

FFR was $-2.7^\circ \pm 13.1^\circ$ (-37.0° to 46.0°) and significant gender differences were observed ($p < 0.001$) (Figure 35). The mean female standing FFR was -5.2° (-37.0° to 46.0°) and 1.7° (-34.0° to 35.7°) for males, indicating that, while standing, females tend to be internally rotated and males tend to be externally rotated. The mean standing FFA was $13.2^\circ \pm 12.2^\circ$ (-27.8° to 52.3°) and significant gender differences were observed ($p < 0.001$) (Figure 36). The mean female standing FFA was 11.7° (-27.8° to 52.3°) and 15.6° (-8.5° to 49.9°) for males. The mean change in FFR from supine to standing was $-2.2^\circ \pm 11.8^\circ$ (-43.0° to 41.9°) and no significant gender differences were observed ($p = 0.18$). The absolute mean change in FFR from supine to standing was $8.7^\circ \pm 7.2^\circ$ (-0° to 43.0°) and no significant gender differences were observed ($p = 0.09$).

Table 13 Tabulated results for all 1008 consecutive patients across supine femoral rotation, anatomic femoral anteversion, standing functional femoral rotation, standing functional anteversion, and the change in functional femoral rotation from supine to standing. *Indicates statistical significance

	Mean (Absolute Mean)	Range	Standard Deviation	p-value (difference between Genders)
Supine Femoral Rotation	0.4°	-34.0° to 31.4°	10.6°	<< 0.001*
Anatomic Femoral Anteversion	15.6°	-24.4° to 68.4°	9.8°	<< 0.001*
Standing Functional Femoral Rotation	-2.6°	-46.0° to 37.0°	13.1°	<< 0.001*
Standing Functional Femoral Anteversion	13.1°	-27.8° to 52.3°	12.2°	<< 0.001*
Change in Functional Femoral Rotation (Supine to Standing)	-2.2° (8.7°)	-43.0° to 41.9°	11.8°	0.18

161 (16%) patients had standing FFA version of greater than 25° (Figure 36 and Figure 37). Considering a combined anteversion (CA) zone of 25° - 45° and a conventional standing cup anteversion of 20° , 72% of patients would fall within the CA zone when anatomic femoral landmarks are considered (AFA), but only 59% fall within the zone when the functional position of the femur (FFA) is considered. Therefore, considering FFA would place an additional 13% of patients at-risk of posterior impingement in a widely targeted CA zone.

460 (46%) patients had standing FFR (internal or external) of greater than 10° (Figure 37). 123 (12%) patients exhibited an increase in external rotation from supine to standing of greater than 10° (Figure 35 and Figure 37). 335 (33%) patients exhibited an absolute change in FFR (internal or external rotation) of greater than 10° (Figure 37). These patients' femoral components would be functionally oriented in an alignment that is considerably different to the alignment when the prosthesis is implanted on the operating table, or when only AFA is considered, and may place them at risk of functional malorientation.

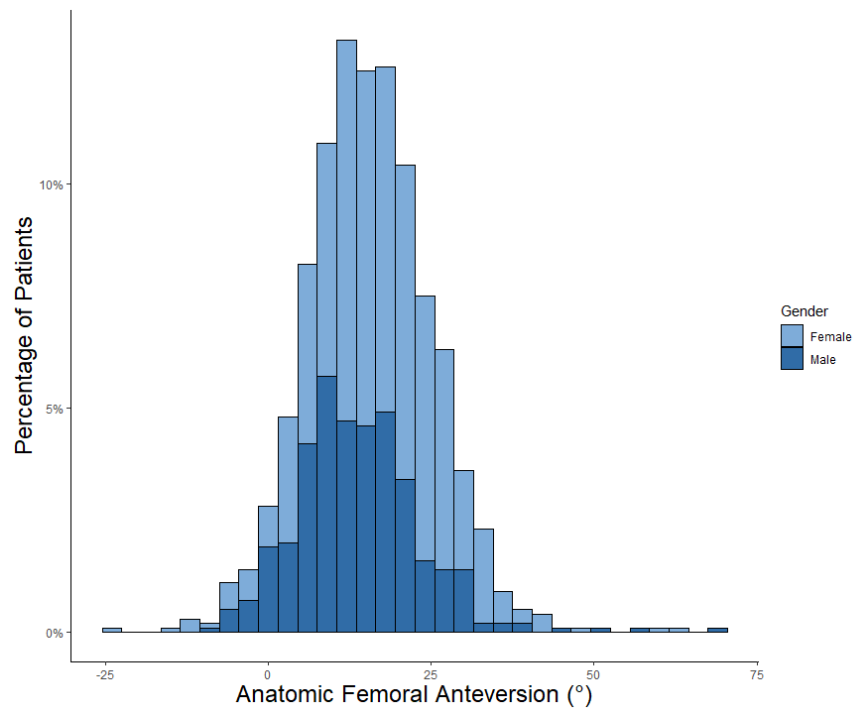


Figure 34 Histogram of the Anatomic Femoral Anteversion results. Courtesy of Hardwick-Morris et al., Arthroplasty Today. Published by Elsevier. This work is licensed under a Creative Commons Attribution – Non-Commercial – No-Derivatives License (CC BY-NC-ND 4.0).

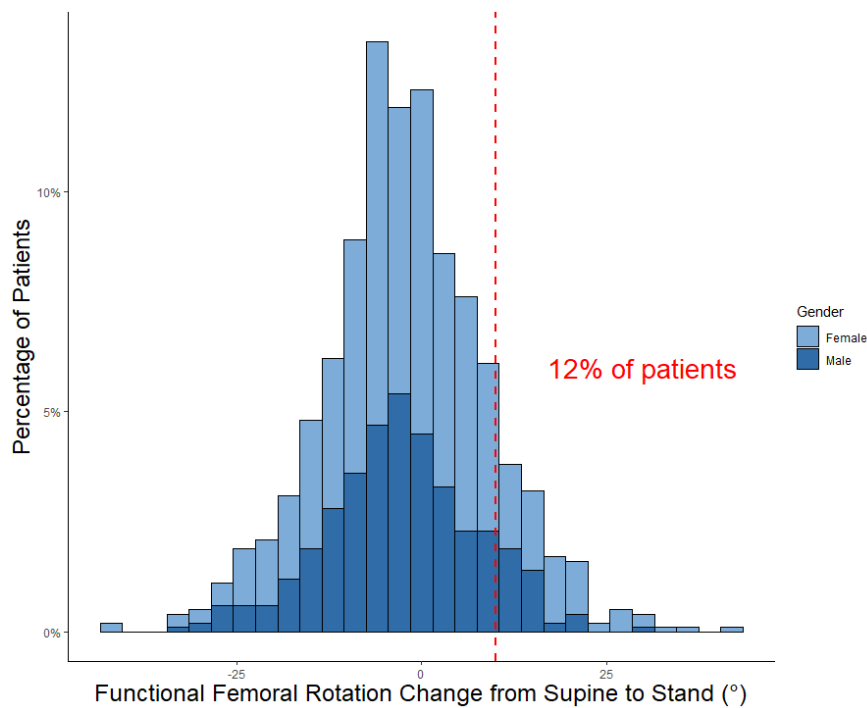


Figure 35 Histogram of the change in Functional Femoral Rotation results. 12% of patients exhibited external femoral rotation from supine to stand of greater than 10°, which may place them at risk of functional malorientation. Courtesy of Hardwick-Morris et al., Arthroplasty Today. Published by Elsevier. This work is licensed under a Creative Commons Attribution – Non-Commercial – No-Derivatives License (CC BY-NC-ND 4.0).

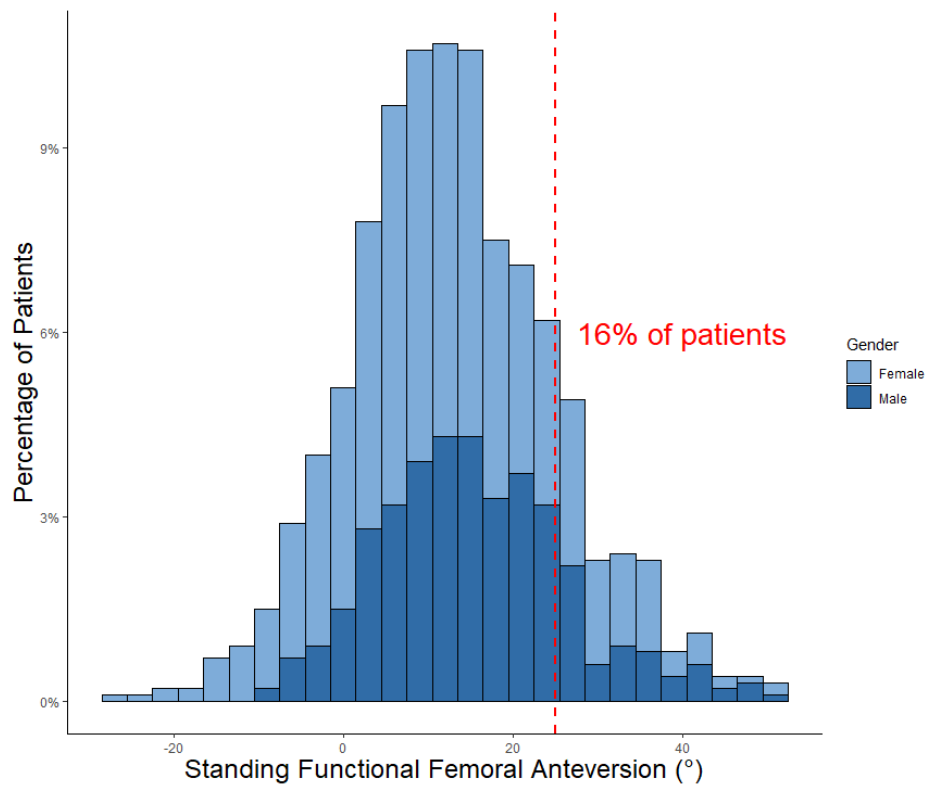


Figure 36 Histogram of the standing Functional Femoral Anteversion results. 16% of patients had functional femoral anteversion of greater than 25°, which may place them at risk of functional malorientation when considered in the context of combined anteversion. Courtesy of Hardwick-Morris et al., Arthroplasty Today. Published by Elsevier. This work is licensed under a Creative Commons Attribution – Non-Commercial – No-Derivatives License (CC BY-NC-ND 4.0).

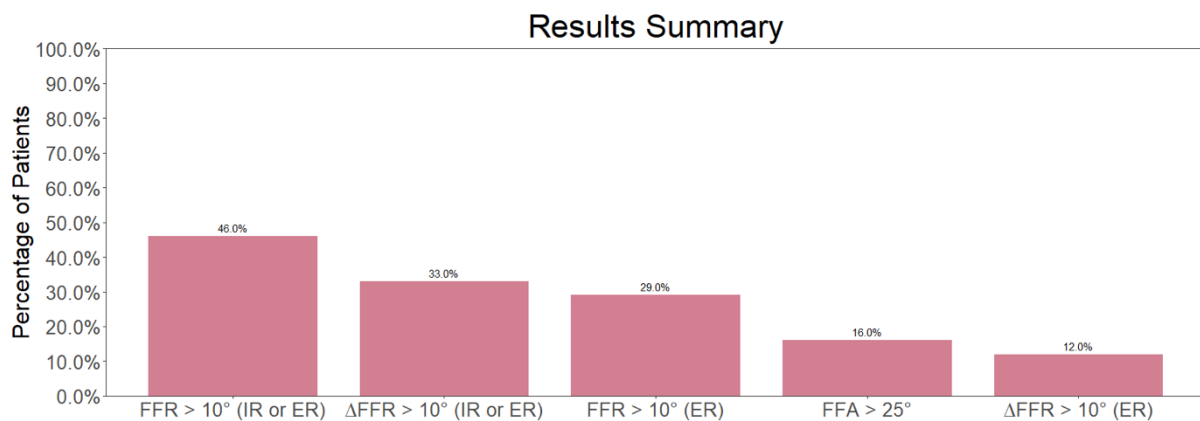


Figure 37 Summary of the key findings for FFR and FFA. IR = internal rotation and ER = external rotation. Courtesy of Hardwick-Morris et al., Arthroplasty Today. Published by Elsevier. This work is licensed under a Creative Commons Attribution – Non-Commercial – No-Derivatives License (CC BY-NC-ND 4.0).

A weak but significant relationship was found with older patients exhibiting less AFA ($p < 0.001$, $R = -0.17$); greater standing FFR ($p < 0.001$, $R = 0.18$); and greater change in FFA from supine to standing ($p < 0.001$, $R = 0.17$). A moderate, negative linear relationship was also observed between AFA and standing FFR ($p < 0.001$, $R = -0.46$), indicating people may externally rotate their femur as AFA decreases with age (Figure 38).

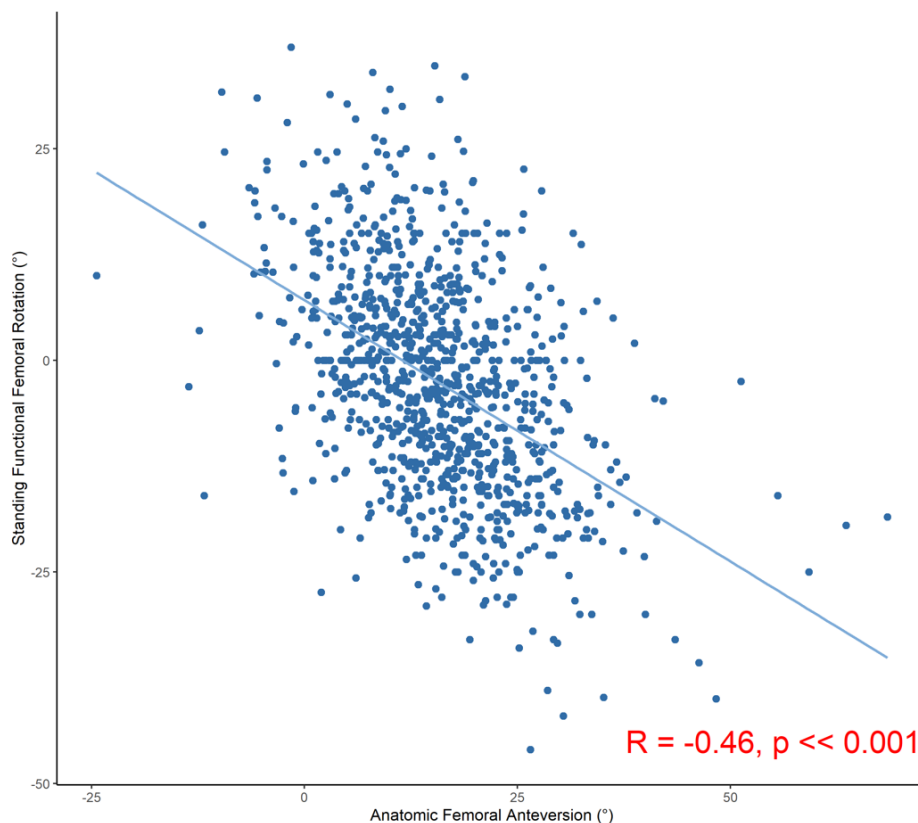


Figure 38 Scatter plot of standing Functional Femoral Rotation and Anatomic Femoral Anteversion and the correlation between these. The statistically significant negative relationship indicates that people may externally rotate their femur as their Anatomic Femoral Anteversion decreases as a compensatory mechanism to maintain soft tissue tensioning. Courtesy of Hardwick-Morris et al., Arthroplasty Today. This work is licensed under a Creative Commons Attribution – Non-Commercial – No-Derivatives License (CC BY-NC-ND 4.0).

Discussion

Functional alignment of the femur in patients requiring THA is under-studied. Several studies have previously investigated AFA,^{17,18,20,187} and how this presents across samples of patients undergoing THA. However, it is known that there is large variation in FFR between individuals and from pre- to post-surgery,^{21,22,188} which AFA does not capture. In this study, the aims were to further investigate FFA, a new measurement explored by Uemura et al.,^{21,22} across a larger sample of patients undergoing THA, assess its implications for femoral stem version targets, and investigate the number of individuals whose femoral rotation may place them at-risk of malorientation.

The results of a mean supine femoral rotation of $0.4^\circ \pm 10.6^\circ$ were similar to studies by Uemura et al.^{21,22} who observed median supine femoral rotations of $-0.4^\circ \pm 10.9^\circ$ ($n = 324$) and $0.3^\circ \pm 8.3^\circ$ ($n = 191$). Both studies by Uemura et al.^{21,22} and the current study demonstrate that, despite having a mean supine rotation value near neutral, the PCL cannot be used as a reference for measuring FFA due to significant inter-patient variability. Additionally, the current study has shown that supine FFR can be over 40° different from standing FFR, 46% of patients have significant standing FFR ($>10^\circ$ internal or external), and 33% of patients undergo significant changes in FFR ($>10^\circ$ of rotation) between positions. Therefore, standing FFR and FFA should not be assumed to be similar to supine FFR.

The results of a mean AFA of 15.6° (-24.4° to 68.4°) with significant gender differences and decreasing with age are comparable to previous assessments of AFA. In a study of 1215 patients requiring THA, Pierrepont et al. found a median AFA of 14.4° (-27.1° to 54.5°) with significant gender differences and decreasing AFA for males with increasing age¹⁸. Similarly, Hartel et al. found a median AFA of 14.2° (-23.6° to 48.7°) and significant gender differences across 1070 patients.¹⁷

As far as the author is aware, previous investigations of standing FFR and the change in FFR from supine to standing are limited to one study by Uemura et al.²². This paper, which assessed pre- and postoperative AFA and FFR, found a mean preoperative supine FFR of $0.3^\circ \pm 8.3^\circ$, mean preoperative standing FFR of $-4.5^\circ \pm 8.8^\circ$, and significant changes between pre- and postoperative states. However, this study did not explore the implications of femoral rotation regarding soft tissue tensioning around the joint or stem version targets, and its findings may be limited to a Japanese population, with the mean AFA of $25.6^\circ \pm 10.6^\circ$ being significantly higher than previously published studies.^{17,18,20,187}

Regarding the soft tissue consequences of femoral rotation, we found a moderate correlation whereby decreasing AFA (which is correlated with increasing age) was associated with increasing external FFR in standing. This indicates the possibility of a compensatory mechanism occurring around the joint where the functional positioning of the femur corrects for anatomical variation,

which could be occurring to maintain tension in the soft tissue around the capsule. Specifically, an individual's FFA may remain roughly constant over time, but their FFR may increase to compensate for a decrease in their AFA.

Previous chapters of this dissertation identified the potential relevance of pelvic rotation in the sagittal plane and femoral rotation in the axial plane – pelvic-femoral kinematics – in the development of iliopsoas tendonitis through the observation of asymptomatic patients with relatively high cup prominence, yet no iliopsoas impingement. Specifically, it was believed that external FFR and anterior pelvic tilt provided favourable kinematics, protecting against iliopsoas impingement. Conversely, it was believed internal FFR and posterior pelvic tilt provided unfavourable kinematics, and would subsequently increase the risk of iliopsoas tendonitis. With evidence from the current study of a compensatory mechanism occurring at the hip joint that can result in changes to postoperative FFR, there are implications for patients where dramatic changes to femoral anteversion are made intraoperatively. Specifically, if a surgeon were to use a modular femoral component to significantly increase the ASA, this may result in the patient internally rotating their femur postoperatively to balance the capsular soft tissue, leading to iliopsoas tendonitis. This risk of iliopsoas tendonitis may be further exacerbated due to the tendency for pelvises to rotate posteriorly after THA surgery,^{189,190} meaning that patients may present years after surgery with iliopsoas irritation due to gradual changes in their hip joint kinematics. Conversely, if a surgeon were to use a modular femoral component to significantly decrease ASA, the patient may respond postoperatively by externally rotating their femur. This would protect against iliopsoas tendonitis; however, it may raise the risk of other complications, such as component-on-component impingement. Although these scenarios are hypothetical, similar ideas have been described by Rivière et al.^{191,192} in studies investigating kinematic alignment of the hip, and a study by Akiyama et al.²⁴. Therefore, further research is warranted to better understand pre- to post-operative changes to pelvic-femoral kinematics, and to investigate clinical differences in patients who undergo large changes to AFA, as this will enable improved preoperative templating protocols.

Further exploring this idea of compensatory mechanisms occurring at the hip, it was noted in the current study that major adjustments to acetabular version from native, although protective for instability and edge-loading, can create gait disturbances, despite no changes to the AFA. The belief is that the significant body of evidence that supports preoperative analysis of the hip-spine relationship^{99,110,193} has led in some instances to dramatic increases in cup anteversion, leading to an uncoupling of the native combined version. Such a patient with significantly increased cup version, but restored anatomic AFA, may have altered gait biomechanics, walk with significant internal rotation due to kinematic disharmony, and present with resultant iliopsoas pain. There is evidence to support this in the study by Uemura et al.²², who observed a mean change in standing FFR from pre- to postoperative configurations of -9.8° (internal rotation). Further study of pre- to

postoperative changes in acetabular anteversion, AFA, and FFR is needed to substantiate these beliefs. However, the concepts of FFR and FFA may help improve surgical prescriptions on both the acetabular and femoral sides.

It has long been recognized that, to achieve optimal alignment and impingement-free ROM in THA, both the femoral and acetabular component orientations should be considered. As such, combined anteversion targets have been proposed.^{194–197} Despite their utility, these zones rarely incorporate pelvic tilt and its impact on functional cup anteversion, and to the author's knowledge have not been previously formulated to consider FFR, referencing only AFA. However, considering femoral anteversion only in relation to anatomic landmarks, as AFA does, could be seen as analogous to only considering the cup orientation in a supine AP radiograph, as it does not provide an understanding of the functional position of the prosthesis. It is now understood that both the pelvis and femur can rotate substantially between functional positions, altering the orientation of the components. Given the degree of variation observed in this study, combined anteversion targets may need to consider FFA instead of AFA, as it was noted that an additional 13% of patients would fall outside a widely cited CA zone when considering the functional alignment of the femur. Therefore, like the adoption of preoperative functional pelvic radiography to understand the patient's pelvic mobility,^{106,110} functional knee imaging should be considered to understand if a patient's functional combined anteversion is significantly different to their anatomic combined anteversion.

This study has several limitations. First, pelvic tilt values were not incorporated and, as such, the patients defined as being 'at risk' due to their FFR from supine to standing may have had a favorable pelvic tilt change that would not place them at risk of impingement. However, this was not seen as consequential as the aims of the paper were to define FFA, demonstrate its high variability across a large sample of patients requiring THA, and discuss its implications for femoral stem anteversion targets in THA. Second, patients were not stratified or excluded based upon pathology. This meant the sample of patients included patients with primary and secondary osteoarthritis, where secondary osteoarthritis may have been associated with Dysplasia, Slipped Capital Femoral Epiphysis, Perthes-Legg-Calves, or other conditions that can dramatically increase a patient's AFA. However, this improves the generalisability of the study as the purpose of the paper was to define the full range of FFA of all patients requiring THA, not specifically for patients with primary osteoarthritis. Third, it should be emphasized that this study contains only preoperative imaging data of patients with pathological hips. It has been shown that pelvic tilt changes from pre- to postoperative states,¹⁸⁹ with greater changes occurring in patients with more anteriorly rotated pelvises. These larger changes are likely due to preoperative hip contractures resolving, which may be a mechanism to reduce pain that is secondary to the patient's arthritis. Therefore, similar phenomena may occur on the femoral side whereby patients excessively rotate their femurs externally or internally to reduce pain and, therefore, their postoperative FFR may

naturally differ from their preoperative FFR. Further research into this is needed to understand which patients may undergo natural changes to their FFR from pre- to postoperative states and our results should be interpreted accordingly. Fourth, there is a degree of inapplicability to surgeons and patients who do not have access to the imaging requirements for the preoperative analysis discussed in our study. However, EOS scans have been shown to accurately determine FFR¹⁹⁸ and present another option of measuring this parameter preoperatively, increasing its accessibility. Further research could also investigate how well FFR can be assessed from preoperative anteroposterior radiographs by using the lesser trochanters as a reference. Finally, this study did not address the extent to which AFA can be changed intraoperatively to achieve a desirable ASA and FSA. Previous studies have shown that a patient's unique femoral morphology dictates the achievable AFA when using metaphyseal-filling, press-fit components, however this is more controllable in cemented or modular stems.^{20,199} Therefore, when using an uncemented femoral component, it may not be feasible to alter FFA significantly. However, preoperative knowledge of a patient's unique femoral morphology using 3D templating can provide surgeons with knowledge of the achievable femoral anteversion with different implant types.

In summary, functional alignment of the femur is under-studied. This study demonstrated that the femur, like the pelvis, can rotate substantially between supine and standing, altering the functional orientation of the femur. These changes in FFR between positions may escalate the risk of prosthetic or bony impingement or may have downstream consequences on soft tissue tensioning when dramatic alterations to femoral or acetabular anteversion are made intraoperatively. Therefore, like the hip-spine relationship, we believe the pelvis-femur relationship plays a significant role in patient outcomes and further research into FFA/FFR may improve both acetabular and femoral component positioning.

CHAPTER 5: DETERMINATION OF PREOPERATIVE RISK FACTORS FOR ILIOPSOAS TENDONITIS AFTER TOTAL HIP ARTHROPLASTY: A SIMULATION STUDY

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Abstract

INTRODUCTION: Iliopsoas tendonitis occurs in between 4-30% of patients after hip arthroplasty and has been thought to only be caused by an oversized cup or cup malpositioning. However, no study has associated the relationship between preoperative measurements with the risk of impingement. This simulation study sought to assess impingement between the iliopsoas and acetabular cup using a novel simulation to determine the risk factors for iliopsoas impingement.

METHOD: 448 patients received lower limb CT scans and lateral x-rays that were segmented, landmarked, and measured using a validated preoperative planning protocol. Implants were positioned according to the preference of ten experienced surgeons. The segmented bones were transformed to the standing reference frame and simulated with a novel computational model that detects impingement between the iliopsoas and acetabular cup. Definitions of patients at-risk and not at-risk of impingement were defined from a previous study. At-risk patients were propensity score matched to not at-risk patients to remove covariate imbalance. The method for matching was a 1:1 nearest neighbour logistic regression matching algorithm that used age and gender as covariates.

RESULTS: 23% of patients were identified as being at-risk of iliopsoas tendonitis. Mean standing pelvic tilt for the at-risk patients was -6.0° and -0.7° for the not at-risk patients. The difference was statistically significant ($p < 0.01$). Mean difference between planned cup size and native femoral head diameter ($\Delta C-NFH$) for the at-risk patients was 5.7mm and 5.1mm for the not at-risk patients. The difference was statistically significant ($p = 0.01$). No statistically significant difference was found for the difference in functional femoral rotation between the two cohorts of patients. Additional simulations of at-risk patients indicated increased anteversion of the acetabular cup reduces impingement risk more effectively than medialisation.

CONCLUSIONS: Impingement between the iliopsoas and acetabular cup is under-studied and may be more common than is published in the literature. It is typically thought to only be related to cup size or positioning. However, this study demonstrated significant differences between at-risk and not at-risk patients in additional measurements, and identified factors that may exacerbate iliopsoas impingement. These results shed light on the relevance of spinopelvic factors to iliopsoas irritation, which could factor into a surgeon's preoperative expectation management of patients who have significant posterior pelvic tilt in standing. Additionally, a previous study observed a similar threshold for $\Delta C-NFH$, which could be factored into preoperative planning to avoid iliopsoas tendonitis.

Introduction

Iliopsoas tendonitis is a soft tissue complication that can have significant adverse impacts on a patient's quality of life after total hip arthroplasty (THA) surgery.^{112,135} Several causes of iliopsoas tendonitis have been described in previous literature, including excessive changes to leg length or offset,¹²⁵ large diameter femoral heads,^{129,133,134,138,139} and protruding screws or cement.^{128,143} However, the most frequent cause of irritation is attributed to impingement between the anterior surface of the acetabular component and the iliopsoas, which arises due to over-sizing; under-anteverting or retroverting; and over-lateralising of the acetabular prosthesis.^{126,127,136} Despite a relatively high incidence of between 4-30% of patients after THA surgery,^{125,126,132} most relevant studies report on the incidence or management of iliopsoas tendonitis through case reports and retrospective database studies. Therefore, there is a lack of literature aimed at preventing this condition or identifying risk factors that may exacerbate it.

Previous chapters of this dissertation have focused on the development and assessment^{175,200} of a computational simulation that can detect impingement between the iliopsoas and acetabular cup using a novel approach to approximate the wrapping path of the iliopsoas. The ambition for this computational model is for it to integrate into a preoperative planning system and contribute to a preoperative planning protocol that optimises component positioning by reducing the likelihood of iliopsoas irritation post-surgery. Therefore, the aim of the current study was to apply the validated simulation to the preoperative setting to determine risk factors that may exacerbate iliopsoas tendonitis.

In the previous study of the simulation in THA patients,¹⁷⁵ it was observed that several asymptomatic patients had relatively high cup prominence, but did not have any iliopsoas impingement measured by the simulation. This indicated that the simulation is capable of differentiating between cup prominence that does lead to iliopsoas impingement, and cup prominence that does not. We believed the reason for this was due to the relative orientation of the pelvis and femur; in other words, spino-pelvic and pelvic-femoral kinematics influence the impingement. Specifically, an anteriorly tilted pelvis and externally rotated femur would provide favourable kinematics and may prevent or reduce impingement between the iliopsoas and acetabular cup. As such, in the current study, it was hypothesised that iliopsoas impingement would be related to kinematic factors, such as pelvic tilt and functional femoral rotation (FFR).

Secondary aims of the study were to assess how the typical intraoperative techniques for reducing the risk of iliopsoas tendonitis – increased anteversion and/or medialising the acetabular cup – influence iliopsoas impingement. Due to the need for three-dimensional (3D) modelling, there is a sparsity of literature directly comparing these strategies for reducing the risk of iliopsoas impingement. However, a 3D simulation study by Ueno et al.,²⁰¹ which assessed how cup prominence changes with posterior rotation of the pelvis, observed that increasing acetabular

anteversion by 8° markedly reduced severe cup prominence. The authors of this study, therefore, suggested that increasing acetabular anteversion was an appropriate strategy to reduce cup prominence. This suggestion was caveated by acknowledging the risk of excessive increases to anteversion in patients with significant posterior pelvic tilt, which would raise the risk of posterior prosthetic impingement and could result in anterior dislocation. Despite the study by Ueno et al.²⁰¹ not assessing the impact of medialising the acetabular component, it was hypothesised in the current study that increased anteversion of the cup would demonstrate a greater reduction in impingement than medialisation of the cup.

Patients and Methods

Ethics for this study was approved by the Bellberry Human Research Ethics Committee (study number 201203710).

This was a retrospective simulation study of 448 patients undergoing THA surgery. 269 (60%) of patients were female. The mean age of patients was 66.8 ± 10.8 (29.3 to 93.8). Inclusion criteria was for patients to be undergoing primary THA surgery with the assistance of 360Hip™ preoperative planning software (360 Med Care, Sydney, Australia). A visualisation of the study process can be found in Figure 39.

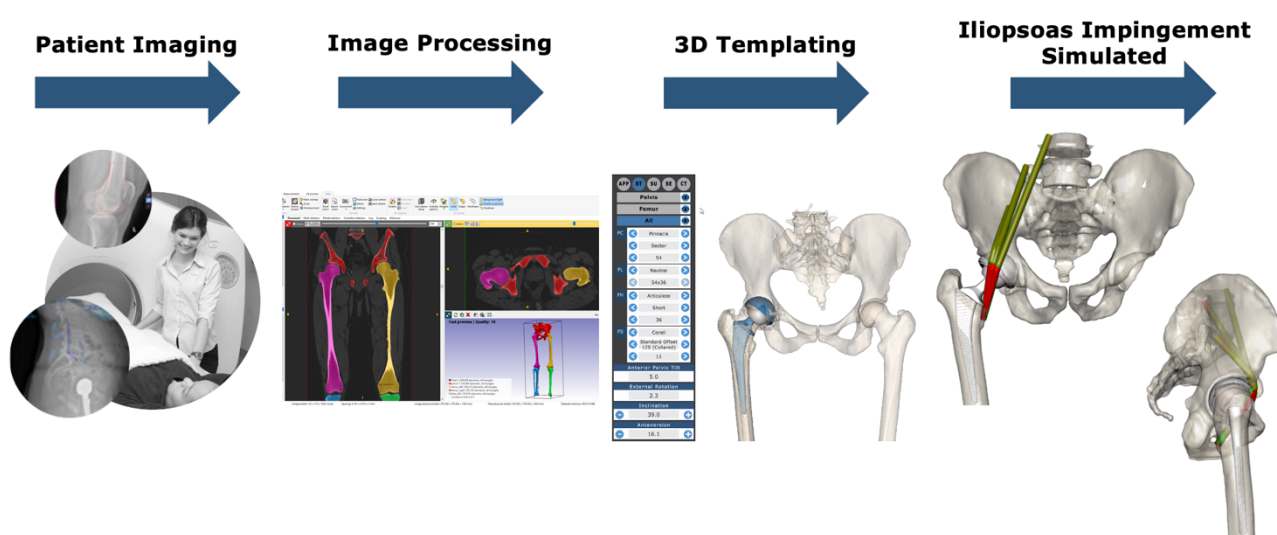


Figure 39 A broad overview of the steps involved from patient imaging through to image processing, 3D templating, and iliopsoas impingement simulation. Reprinted with permission from John Wiley & Sons, Inc.

All patients underwent a validated and regulated preoperative imaging protocol that included a lower-limb CT scan, weightbearing (WB) anteroposterior (AP) pelvic x-ray, lateral standing pelvic x-ray, and lateral standing knee x-ray. 3D reconstructions of the bony anatomy were generated and

landmarked from the CT scan using ScanIP R-2020.09 (Synopsys, California, USA). 3D templating was performed in proprietary software using a Depuy Corail/Pinnacle implant combination. Implant positioning for this study was standardised across all patients according to the following protocol: 40°/20° standing acetabular cup orientation; recreation of native COR and hip lengthening to restore preoperative leg length discrepancy (LLD) identified on the WB AP x-ray; and recreation of anatomic femoral anteversion. Component sizing was performed by surgical planning engineers at 360 Med Care according to a validated internal protocol. Each case undergoes quality checking by a second engineer to confirm the component sizing, and preoperative reports are issued to the treating surgeon for final approval. It should be noted that parameters other than component sizing on the preoperative reports may have differed to those used in this study as patient-specific changes to parameters, such as acetabular orientation or COR, may have been made to the final preoperative plans to address specific patient anatomy or kinematics. For example, the acetabular anteversion on a preoperative report for a patient may have been increased or decreased to optimise for patient spinopelvic kinematics.

The 3D reconstructions of the bony anatomy were transformed to the standing reference frame using the pelvic tilt and functional femoral rotation (FFR) measured on the lateral x-rays and each patient was simulated in the novel computational model that has been demonstrated to accurately detect iliopsoas impingement. The method for determining preoperative FFR is outlined in a study by Hardwick-Morris et al.²³ and a detailed explanation of the iliopsoas impingement detection simulation can be found in a previous case-controlled assessment of the simulation.¹⁷⁵

Patients who were at-risk of iliopsoas tendonitis were defined as those with greater than 0.16mm of maximum impingement between the iliopsoas and acetabular cup, which was identified as the optimal cut-off point using a logistic regression model in the previous study.¹⁷⁵ This cut-off point was shown to have a sensitivity of 74%, specificity of 100%, and an AUC of 0.86 in THA patients. At-risk patients were propensity score matched to patients who were not at-risk of iliopsoas tendonitis to remove covariate imbalance and improve statistical comparison between the cohorts. The method for propensity score matching was a 1:1 nearest neighbour logistic regression matching algorithm that used age and gender as covariates.

The parameters compared between the patient cohorts included: standing pelvic tilt (positive values corresponding to anterior pelvic tilt), native femoral head diameter, acetabular cup diameter, anatomic femoral anteversion, the difference between the planned acetabular cup diameter and native femoral head diameter (ΔC -NFH), and FFR (positive values corresponding to external femoral rotation). Standing pelvic tilt was investigated due to its observed link to cup prominence,²⁰¹ whereby increased posterior pelvic tilt results in increased cup prominence. The delta between cup size and native femoral head diameter was assessed due to Odri et al.¹³⁶ observing an odds ratio of 26 for iliopsoas impingement when the implanted acetabular component

was greater than 6mm larger than the native femoral head diameter. Anatomic femoral anteversion and FFR were included in the analysis due to the suggestion by Akiyama et al.²⁴ that increased femoral anteversion has the effect of shifting the femur posteromedially, which we believe would create a more acute wrapping angle of the iliopsoas around the acetabular margin and increase the likelihood of impingement between the iliopsoas and acetabular cup.

Both acetabular cup orientation and position have been shown to influence cup prominence.^{136,201,202} Therefore, to determine the individual and combined influences of cup position and orientation on iliopsoas impingement, the at-risk patients underwent additional simulations. Inclination was not assessed as this was shown by Ueno et al.²⁰¹ to have a markedly lower impact on cup prominence. These additional simulations included modelling the iliopsoas impingement at cup orientations of 40°/25° and 40°/30°; and then medialising the cup by 3mm from the COR and orienting the cup at 40°/20°, 40°/25° and 40°/30°. Therefore, each at-risk patient underwent an additional five simulations of iliopsoas impingement with various cup positions.

Statistical analysis

Statistical analysis was performed in R Studio v1.3.1903 (Boston, MA, USA). An alpha value of 0.05 was used to determine clinical significance. Shapiro-Wilk tests were performed to determine whether measurements were normally distributed or not. For normally distributed data, two-way, independent-samples t-tests were used to determine significant difference for continuous variables. For data that was not normally distributed, Mann-Whitney U tests were used to determine significant difference between continuous variables. For categorical variables, Chi-Squared tests were used to determine significant difference.

Results

104 (23%) patients were observed to have greater than 0.16mm of maximum iliopsoas impingement. These 104 patients were, therefore, identified as being at-risk of iliopsoas tendonitis based on the templated implant positions. As described in the methods, these patients were propensity score matched to not at-risk patients based on age and gender.

Median impingement for the at-risk patients was 0.81mm and 0.00mm for the not at-risk patients. The difference was statistically significant ($p < 0.01$). Median standing pelvic tilt for the at-risk patients was -6.0° and -0.7° for the not at-risk patients. The difference was statistically significant ($p < 0.01$). Median Δ C-NFH for the at-risk patients was 5.7mm to and 5.1mm for the not at-risk patients. The difference was statistically significant ($p = 0.001$). Median native femoral head diameter for the at-risk patients was 46.2mm and 47.5mm for the not at-risk patients. The difference was not statistically significant ($p = 0.31$). Median anatomical femoral anteversion for the at-risk patients was 14.4° and 13.3° for the not at-risk patients. The difference was not statistically significant ($p = 0.69$). Median planned cup diameter for the at-risk patients was 52mm, and 52mm

for the not at-risk patients. The difference was not statistically significant ($p = 0.29$). Median FFR for the at-risk patients was 1.3° and -0.3° for the not at-risk patients. The difference was not statistically significant ($p = 0.35$). The results can be found in Table 14.

Table 14 Tabulated results of the parameters used to compare the patients identified as being at-risk of iliopsoas tendonitis from the simulation, and the patients propensity score matched patients to them. * indicates statistical significance, n.s = not significant, † = student's t-test, ‡ = chi-squared test, § = Mann-Whitney U test.

Parameter	Median of at-risk patients	Median of not at-risk patients	p-value
Maximum impingement	0.81mm	0.00mm	$p < 0.01^*\S$
Standing pelvic tilt	-6.0°	-0.7°	$p < 0.01^*\S$
Δ Cup-Native femoral head diameter	5.7mm	5.1mm	$p = 0.001^*\S$
Native femoral head diameter	46.2mm	47.5mm	n.s§
Anatomic femoral anteversion	14.4°	13.3°	n.s§
Cup diameter	52mm	52mm	n.s‡
Functional femoral rotation	1.3°	-0.3°	n.s†

As mentioned in the Methods, additional iliopsoas impingement simulations were run for the patients identified as at-risk. The number of patients in these additional simulations that were identified as being at-risk of iliopsoas tendonitis due to having a maximum impingement of greater than 0.16mm was as follows: 67 patients with the acetabular cup positioned at $40^\circ/25^\circ$; 21 patients with the acetabular cup positioned at $40^\circ/30^\circ$; 87 patients with the acetabular cup positioned at $40^\circ/20^\circ$ and medialised by 3mm; 38 patients with the acetabular cup positioned at $40^\circ/25^\circ$ and medialised by 3mm; and 13 patients with the acetabular cup positioned at $40^\circ/30^\circ$ and medialised by 3mm. Therefore, an increase in anteversion from 20° to 25° led to a 36% reduction in the number of patients at-risk of iliopsoas tendonitis, whereas a 3mm medialisation of the cup only led to a 16% reduction. When the anteversion was increased from 20° to 25° and the cup was medialised by 3mm, a 63% reduction in the number of patients at-risk of iliopsoas tendonitis was observed. These results can be seen in Figure 41 and Table 15. The amount of impingement observed for each cup orientation and position can also be found in Figure 40 and Table 15.

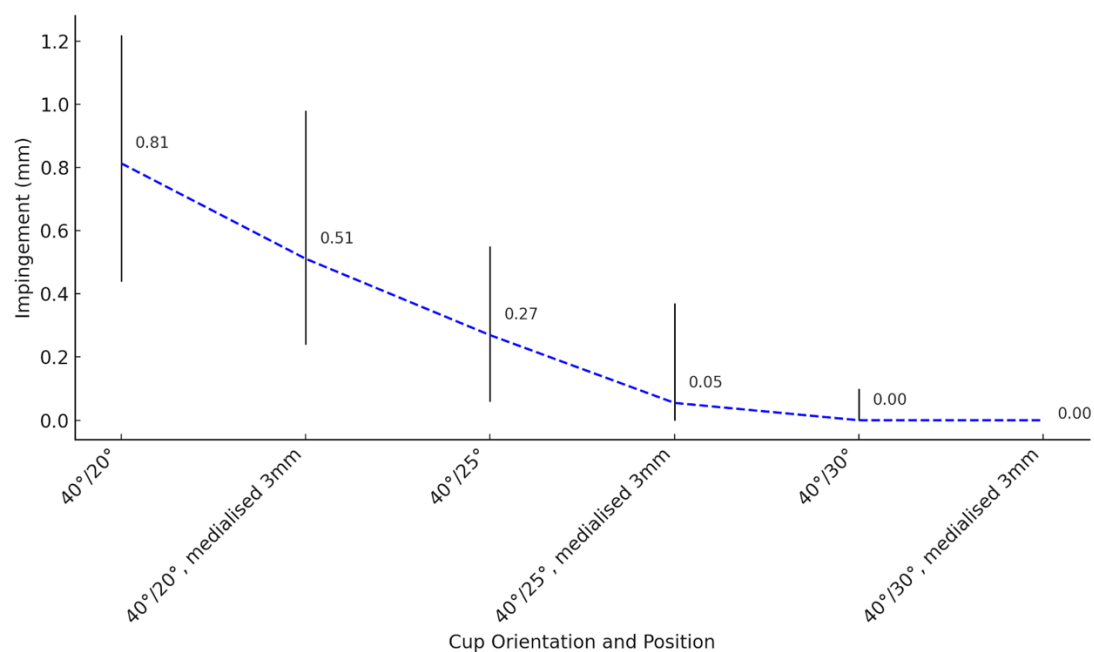


Figure 40 Plot of the median impingement values observed in the initial cohort of 104 at-risk patients for all simulations with different acetabular positions and orientations. Error bars show the interquartile range. Reprinted with permission from John Wiley & Sons, Inc.

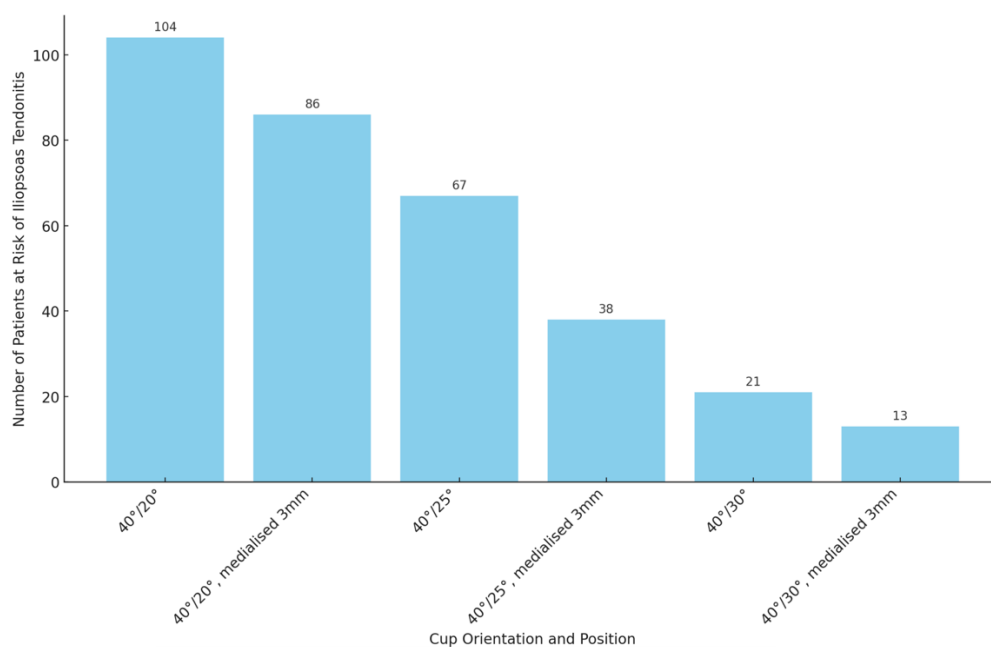


Figure 41 Number of patients at-risk of iliopsoas tendonitis with different cup orientations and positions. Reprinted with permission from John Wiley & Sons, Inc.

Table 15 Tabulated results of the additional iliopsoas impingement detection simulations run for the patients initially defined as at-risk.

Simulation parameters of acetabular cup	Number of patients at-risk of iliopsoas tendonitis	Reduction in number of at-risk patients (%)	Median impingement (mm)	Interquartile range (mm)
40°/20°	104	n/a	0.81	0.44 – 1.22
40°/20°, medialised 3mm	86	17	0.51	0.24 – 0.98
40°/25°	67	36	0.27	0.06 – 0.55
40°/25°, medialised 3mm	38	63	0.05	0.00 – 0.37
40°/30°	21	80	0.00	0.00 – 0.10
40°/30°, medialised 3mm	13	87	0.00	0.00 – 0.00

Discussion

Iliopsoas tendonitis is relatively common after THA surgery,^{125,126,132} and may in fact be more common than is published in the literature due to limitations of the retrospective studies that document its incidence¹³⁵ and changing surgeon practises.¹⁴⁰ Additionally, findings from recent studies highlight a complex relationship between iliopsoas tendonitis, cup prominence, and postoperative groin pain. These findings include acetabular cup prominence being linked to postural factors, such as pelvic tilt;²⁰¹ the psoas muscle index (a height-adjusted measurement of the cross-sectional area of the iliopsoas at the L3 level) and sagittal spinal imbalance being linked to an artificial hip perception;¹⁷⁷ and a potential link between spino-pelvic and pelvic-femoral kinematics with iliopsoas impingement.¹⁷⁵ Despite this, iliopsoas tendonitis is under-studied, particularly from the standpoint of computational modelling and preventative measures.¹⁷⁵ To address this need for computational consideration of soft tissue structures before and after hip arthroplasty, earlier chapters of this dissertation focused on developing a simulation for detecting iliopsoas impingement, and then demonstrating its predictive power for the detection of iliopsoas tendonitis using postoperative, representative data.^{175,200} The current study intended to utilise this simulation in the preoperative context to identify risk factors that may exacerbate the risk of iliopsoas tendonitis by increasing iliopsoas impingement. These risk factors might then assist in preoperative planning for THA surgery by identifying patients for whom there is a greater risk of postoperative iliopsoas irritation.

The key findings in the current study were that patients at-risk of iliopsoas tendonitis had significantly more posteriorly tilted pelvises in standing, and significantly larger differences between cup and native femoral head diameters. Interestingly, similar results of the difference between cup diameter and native femoral head diameter were observed by Odri et al.¹³⁶ who found an odds ratio (OR) of 26 for iliopsoas impingement pain when the cup diameter was greater than 6mm larger than the native femoral head. This coalescing around a cut-off value of 6mm strengthens the

case for its accuracy and this value could function as a simple threshold for surgeon's to use preoperatively (when a CT scan is available) or intraoperatively with the use of callipers when seeking to reduce the risk of iliopsoas tendonitis.

Regarding the greater posterior pelvic tilt in the at-risk cohort of patients, this is likely due to the gradual opening-up of the acetabular component edge to the wrapping path of the iliopsoas that occurs with increasing posterior pelvic tilt, an illustration of which can be seen in Figure 42. In a patient, it is hypothesised that greater posterior pelvic tilt may further irritate the iliopsoas by lengthening it, relative to a more anteriorly tilted pelvic position, in addition to creating a more acute wrapping angle around the pelvic bone that may result in pain. Following this, if iliopsoas tendonitis is linked to posterior pelvic tilt, iliopsoas-related pain may manifest in some patients years after surgery due to the general trend for pelvises to posteriorly rotate in standing as people age.¹⁸⁹ It should also be noted that this link between the orientation of the pelvis and iliopsoas impingement may explain why some patients with acetabular cup uncoverage do not experience iliopsoas irritation. Specifically, these patients may have an anteriorly tilted pelvis, which prevents the iliopsoas from impinging with the acetabular cup.

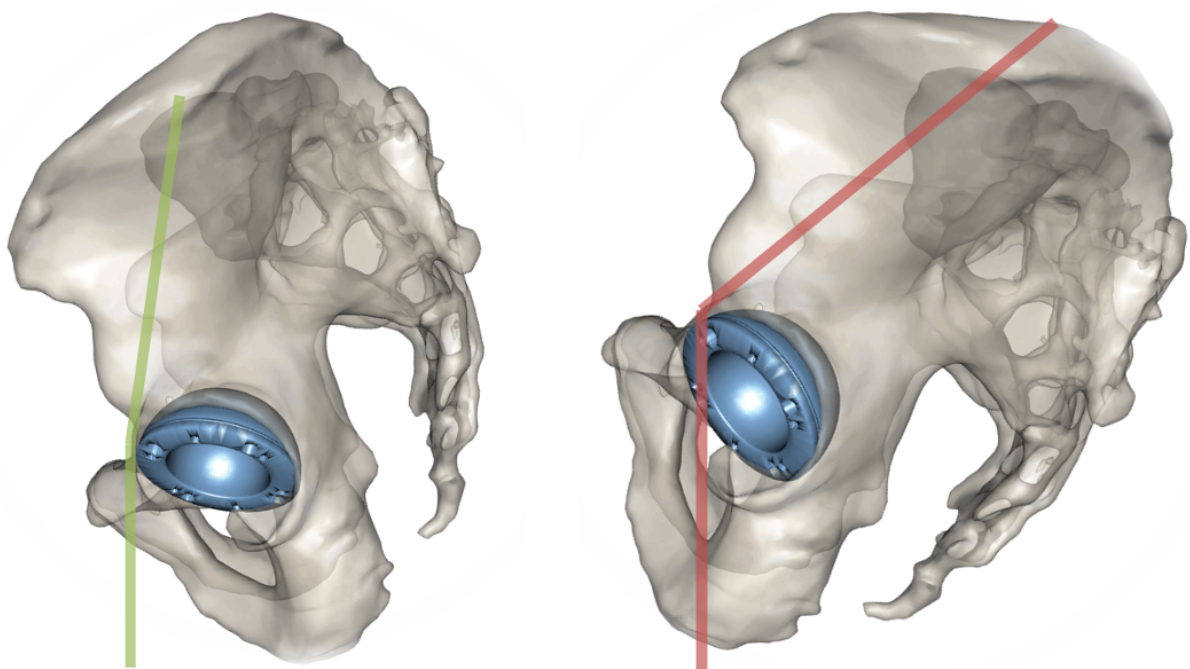


Figure 42 Schematic to demonstrate the impact of posterior pelvic tilt on the risk of iliopsoas impingement with an exposed acetabular cup. (Left) The pelvis is in an anteriorly tilted position, and the iliopsoas, represented by the green line, does not impinge with the cup. (Right) The pelvis is in a posteriorly tilted position, and the iliopsoas, represented by the red line, does impinge with the cup. Reprinted with permission from John Wiley & Sons, Inc.

It was hypothesised that internal FFR may be a preoperative risk factor for iliopsoas tendonitis due to internal FFR's effect of posteriorising the inferior iliopsoas insertion point, which we believed would have a similar effect to posterior pelvic tilt. However, this hypothesis was not corroborated in the results, potentially due to the large degree of internal FFR that may be required to induce impingement between the iliopsoas and acetabular cup. It should be noted that the inclusion of FFR as a potential risk factor for iliopsoas tendonitis was a strength of this study as no prior study has investigated the link between these.

To assess the specific contributions of cup anteversion and medialisation of the cup, additional simulations were run on the 104 at-risk patients identified from the initial simulation. As hypothesised, both increased anteversion and medialisation of the cup led to a reduction in impingement. Notably, the increase in anteversion led to a more pronounced reduction in impingement levels, which suggests that increasing anteversion may serve as a more effective strategy in mitigating the risk of postoperative iliopsoas impingement. However, it is important to consider the impact of any adjustments to cup orientation on the joint's range of motion. For instance, overly aggressive increases to anteversion could lead to posterior prosthetic impingement and anterior instability. Therefore, surgeons should balance any potential soft-tissue benefits of increased anteversion with the patient's biomechanical requirements to ensure joint stability.

There are several limitations to this study that need acknowledgment. First, being a simulation study, the patients defined as 'at-risk' from the simulation may not necessarily experience postoperative iliopsoas tendonitis if the components were implanted in the templated positions. However, in previous studies, the simulation demonstrated a high sensitivity and specificity for distinguishing patients that were diagnosed with iliopsoas tendonitis from patients that were not diagnosed with iliopsoas tendonitis. Therefore, the cut-off used to stratify patients into at-risk and not at-risk in this study was deemed sufficient. Second, final implant sizes chosen intraoperatively by the surgeon may differ. The preoperative planning protocol used in this study has demonstrated correct implant sizing to within ± 1 size over 90% of the time. However, if a smaller diameter acetabular cup were implanted, there would be less risk of the patient experiencing iliopsoas tendonitis, and, conversely, a larger acetabular cup would increase the risk of iliopsoas tendonitis due to the increased risk of cup overhang. Third, due to all patients being simulated with a standardised implant combination at a standardised position, our results, such as the number of patients defined at-risk of iliopsoas tendonitis, may differ significantly from surgeons who use a different implant set and a different protocol or targets for positioning the implants. Fourth, for the purposes of the additional simulations to establish the contributions and influences of anteversion and medialisation on iliopsoas impingement, 3mm of medialisation and 5° changes in anteversion were viewed as somewhat equivalent. However, we acknowledge that different surgeons and researchers may view this differently and believe that changes to the centre of rotation or changes

to cup orientation may be much more detrimental than the other to postoperative joint stability. Finally, the use of a static (standing) pelvic radiographs only permitted assessment of iliopsoas impingement at a singular postural position. However, the pelvis and femur have been shown to rotate significantly between functional positions.^{23,74} Therefore, future analyses may benefit from modelling how iliopsoas impingement varies across different pelvic and femoral orientations throughout a gait cycle, or other dynamic movements, such as getting out of a car or walking up stairs.

To conclude, iliopsoas tendonitis is more complex than simply being related to the presence of cup uncoverage and may be exacerbated by postural factors. Our results of significant differences in pelvic tilt between matched cohorts highlights the 3D nature of this phenomenon and may explain why patients with favourable pelvic tilt, who have anterior cup uncoverage, do not experience iliopsoas tendonitis. We also found a similar cup size threshold to Odri et al.¹³⁶ that could be factored into preoperative planning to avoid iliopsoas tendonitis. Finally, significant differences between the matched cohorts in standing pelvic tilt may shed light on the relevance of spinopelvic factors to iliopsoas irritation, which could factor into a surgeon's preoperative counselling and expectation management of patients who have significant posterior pelvic tilt in standing.

CHAPTER 6: DISCUSSION, FUTURE WORK, AND CONCLUSIONS

Discussion

Despite its relatively high incidence, iliopsoas tendonitis remains an under-studied complication of hip arthroplasty. Studies of iliopsoas tendonitis have typically focused on retrospective database studies that assess incidence and approaches to treatment. There is sparse literature in regards to preventative measures and, as far as the author is aware, no prior studies attempting to simulate the impingement between the iliopsoas and acetabular cup, nor any current products that integrate soft tissue assessments into preoperative planning. Therefore, this dissertation sought to develop and validate a computational simulation that can predict iliopsoas tendonitis in patients undergoing hip arthroplasty surgery utilising an algorithm that calculates iliopsoas impingement instantaneously, and which has the potential to be deployed in a preoperative planning platform. Furthermore, it sought to identify risk factors that may exacerbate the risk of iliopsoas tendonitis to assist clinicians with expectation management of patients pre-surgery.

A summary of the key findings is as follows:

- ◇ Chapter 2 was a retrospective, case-controlled investigation with the primary objective of assessing the accuracy of the iliopsoas impingement detection simulation in THA patients. The key results were the highly significant differences ($p < 0.01$) in the levels of impingement between the symptomatic and asymptomatic cohorts, demonstrating the model's validity in identifying iliopsoas impingement that results in tendonitis, in addition to the improved sensitivity, specificity, and AUC in the ROC curves compared to the typical measurement used to identify iliopsoas impingement – cup prominence.
- ◇ Chapter 3 a similarly designed retrospective, case-controlled investigation with two primary aims. First, to assess the accuracy of the iliopsoas simulation in HRA patients. Second, to compare the results of the symptomatic HRA patients with the symptomatic THA patients, with the hypothesis that greater levels of impingement would be observed in the HRA patients. The key findings of this chapter were the highly significant differences ($p < 0.01$) in the levels of impingement between the symptomatic and asymptomatic cohorts, and the observation that the symptomatic patients demonstrated greater levels of impingement than the HRA patients.
- ◇ Chapter 4 turned the focus to the preoperative setting by investigating functional femoral anteversion (FFA) in a large cohort of patients undergoing THA surgery. The primary aims of this study were three-fold. First, to validate a new approach to measuring FFA using

preoperative lateral knee radiographs. Second, to further explore the variability of FFA, which had previously been studied by Uemura et al.^{21,22} in a Japanese cohort. And third, to examine the data for evidence of soft tissue compensatory mechanisms occurring at the hip joint to balance capsular tension in response to changes in anatomy. The key finding of this study was the significant correlation between decreasing anatomic femoral anteversion (AFA) with increasing external functional femoral rotation, indicating that as people age, and arthritis causes a decrease in the patients native femoral anteversion, people may subsequently externally rotate their femurs to balance the capsular tension. This provided preliminary evidence for the link between pelvic-femoral kinematics and its effects on soft tissue structures around the hip joint.

- ◇ Chapter 5 was a preoperative simulation-based study that involved modelling iliopsoas impingement in over 450 unique patient anatomies with a standardised implant combination and position. Patients were identified as at-risk or not at-risk based on a previously defined threshold in Chapter 2, and the at-risk patients were propensity score matched to not at-risk patients based on age and gender. Several parameters, including standing pelvic tilt, functional femoral rotation, and the delta between cup size and native femoral head diameter ($\Delta C-NFH$) were compared between the cohorts to determine preoperative risk factors. The key findings of this chapter included the highly significant difference in pelvic tilt, with at-risk patients exhibiting more posteriorly rotated pelvises; and the significant difference in $\Delta C-NFH$, with at-risk patients having a roughly 6mm difference between the planned cup size and native femoral head diameter.

Limitations

The novel findings of each chapter in this dissertation must be considered within the context of its limitations. First, the iliopsoas impingement detection simulation developed and validated in this dissertation defined the iliopsoas by landmarks and employed a novel approach to representing the iliopsoas muscle using a convex hull; it did not model the actual anatomy of the iliopsoas. The purpose for this was two-fold. First, it permitted development an algorithm that could execute instantaneously, which encourages its future integration into a preoperative planning platform. Second, it permitted modelling the iliopsoas in different functional positions, according to the orientation of the bony anatomy that the iliopsoas is attached to. However, the key limitation of this is that the modelled path of the iliopsoas may not be representative of the patient's actual anatomy, with the implication of this being that the area of contact between the modelled iliopsoas and the actual iliopsoas is different in-vivo. Specifically, a patient may have an iliopsoas that is wider or narrower at the point where it wraps around the superior acetabular margin of the pelvis. If the actual anatomy of the iliopsoas were to be wider, there may be an increased risk of iliopsoas tendonitis not captured by the model as there is a greater chance of contact between it and the

acetabular cup. Conversely, if the actual iliopsoas were to be narrower, there may be a reduced risk of iliopsoas tendonitis. Comparison of the simulation's representation of the iliopsoas against actual patient anatomy was not pursued as this was believed to be an inaccurate and invalid comparison for two main reasons. First, this would have required segmentation of the iliopsoas from CT scans, which in itself is of limited accuracy due to difficulties in isolating soft tissue structures from CT. Second, and more importantly, the key results from the simulation were the impingement results in functional positions, such as standing, and the CT scan would only permit comparison against a iliopsoas in its supine orientation. Instead, it was believed that correlating the outcome of the simulation (iliopsoas impingement) with clinical outcomes (symptomatic and asymptomatic patients) would yield an appropriate reflection of the model's accuracy in representing the anatomy of the iliopsoas. Despite this limitation, the iliopsoas impingement detection simulation developed by this dissertation demonstrated high sensitivity, specificity, and area under the curve (AUC) of the receiver operating characteristic (ROC) curves in Chapters 2 and 3. Further, the maximum impingement value (as opposed to the mean impingement value) was shown to have greater predictive power of iliopsoas tendonitis, and the three segments that were used to represent the iliopsoas were believed to sufficiently (and repeatedly) capture a superior, central, and inferior point of potential impingement between the iliopsoas and acetabular cup. Therefore, it was believed that even in cases where the iliopsoas is wider or narrower than the simulated iliopsoas, the impingement output by the model would still closely approximate the true amount of impingement.

Second, the simulation does not compute the actual impingement between the iliopsoas and acetabular cup. Instead, it uses a proxy measurement for iliopsoas impingement by measuring the amount of 'stretch' of the iliopsoas due to the acetabular cup. In other words, the difference between the length of the wrapping path of the iliopsoas with and without the presence of an acetabular cup. This approach was taken for similar reasons as above – the desire to develop a simulation that executes instantaneously and allows for manipulation of the bony anatomy and simulated soft tissue anatomy in various functional positions – as modelling the specific interaction between the iliopsoas and acetabular cup would require accurate 3D reconstructions of the patient's soft-tissue anatomy, which is likely less accurate than segmentation of bony tissue due to the lower Hounsfield units, and would require significantly more computing to assess the interaction between the iliopsoas and acetabular cup at a patient-specific level. Further, modelling the patient-specific interaction between the iliopsoas and acetabular cup would require several assumptions about the behaviour of the soft tissue, with requisite knowledge about the transition from muscle to tendon of the iliopsoas tendon that may not be possible from CT, and it was hypothesised by the author that these increases in complexity would not provide additional clinical benefit to the simulation. Despite this, machine-learned algorithms for automatic segmentation of soft tissue anatomy from CT scans presents a viable path for improved soft tissue-related simulations in orthopaedics research, and further research here is warranted.²⁰³

Third, due to only having (routine) static imaging available, iliopsoas impingement was only modelled at static points. Specifically, CT scans capture the orientation of the patient's bony anatomy in a supine position, and lateral standing x-rays enabled transformation of the bony anatomy to a functional standing position. This prevented simulation of the changes in iliopsoas impingement throughout functional movements, such as walking or getting out of a car (known irritants of iliopsoas^{112,135}). However, this could, theoretically, be achieved with some basic assumptions about the changes in functional femoral rotation and pelvic tilt between known endpoints and may lay the groundwork for future study into this area. For example, if the iliopsoas impingement detection simulation were to be used in the context of preoperative planning and, due to various anatomical features, the risk of iliopsoas tendonitis could not be removed, such as in a patient with hip dysplasia and a shallow acetabulum, various functional movements could be simulated to determine which movements would create the most risk of irritation. This data could be provided to the surgeon, who could counsel their patient about expectations post-surgery. For example, the surgeon could inform the patient that they may experience irritation when getting out of a chair, but not when walking or running.

Fourth, assessment of the iliopsoas impingement detection simulation's accuracy was achieved through postoperative, retrospective data, which may have introduced bias into the development of the model. To acquire higher-level evidence of the simulation's accuracy and validity, a prospective trial would need to be undertaken whereby a risk of iliopsoas tendonitis would be preoperatively assigned to patients undergoing THA surgery through integration of the simulation into a routine preoperative planning protocol. All patients would then need to be followed-up 6-12 months later and consulted by their surgeon as to whether they have experienced groin pain, and what the nature of that pain is. Postoperative CT data would be required to ascertain the final position of the implanted components, and the iliopsoas impingement detection simulation could then be re-executed on the postoperative data as the final implant positions will be different from the preoperative plan. This comprehensive dataset would allow assessment of the model's true accuracy of predicting patients who are likely to experience iliopsoas tendonitis, in addition to further assessing the simulation's accuracy in patients who do experience iliopsoas tendonitis. Furthermore, it would permit prospective assessment of the severity, location, and nature of patients' iliopsoas pain. Investigations could then be undertaken to determine if there is a correlation between descriptions of pain and the impingement observed by the simulation. Despite the potential benefits of undertaking a study like this, it would take several years to recruit the necessary number of patients, in addition to exposing patients to potentially unnecessary ionising radiation from the postoperative CT scan.

Fifth, due to the absence of routine preoperative CT imaging, there was no assessment of the change in iliopsoas length from preoperative to postoperative states. Had this imaging been available, simulation of the iliopsoas using preoperative and postoperative data could have

provided insight into the routine change in iliopsoas length in both symptomatic and asymptomatic patients. To ensure accuracy, this could have been undertaken with the same set of landmarks used to define the insertion points of the iliopsoas from the postoperative CT imaging by registering the postoperative bony anatomy to the preoperative anatomy, and applying the corresponding Euler transformation to the landmarks to simulate the preoperative iliopsoas. Further, if simulation of the preoperative iliopsoas muscles was performed, changes to hip length and offset and their contribution to iliopsoas tendonitis could have been investigated. This may have provided evidence for cause of iliopsoas tendonitis in some of the symptomatic patients who did not have any impingement observed by the simulation. Despite this, it would have been hypothesised by the author that, in patients who underwent THA surgery, there would have been a trend towards a decrease in the length of the iliopsoas due to the reduced femoral head size. Further, the author believes this would have held true even in symptomatic patients with impingement between the iliopsoas and acetabular cup. However, in patients underwent HRA surgery, it would have been hypothesised that the lengths of the pre- and postoperative iliopsoas muscles would have been roughly equivalent due to the larger femoral head size of HRA implants. Research in this area has been performed by Jeffers et al.²⁰⁴ who found increased range of motion at the hip joint after transpelvic implantation of THA components in cadavers due to a reduction in the femoral head size. The suggestion of the authors here was that increases in hip length of offset may be needed to maintain the capsular tension.

Sixth, a significant limitation of the simulation developed in this dissertation is its requirement of a CT for the generation of the 3D bony anatomy. Although preoperative CT imaging is likely to become more routinely available with the increased uptake of assistive technologies,²⁰⁵ they add to the costs of surgery, and AP pelvic radiographs remain the current standard of care. Therefore, for wider uptake of this tool, development of a secondary tool that utilises 2D-3D reconstruction from standard pelvic radiographs may need to be undertaken. However, due to the high-degree of accuracy required for the 3D bony anatomy to ensure accuracy of the iliopsoas impingement detection simulation, combined with the errors associated with 2D-3D reconstruction, this presents a significant challenge to wider adoption.

It is also worthwhile discussing the additional information that is attained from the use of the simulation over the use of imaging alone (either CT or lateral radiographs). As has been noted throughout the thesis, iliopsoas tendonitis is a complex, multi-factorial, and three-dimensional complication. This has been noted through the observation of asymptomatic patients with non-trivial levels of cup prominence who do not demonstrate iliopsoas impingement, which likely resulted from the patient's bony anatomy being functionally oriented in positions that are 'protective' against iliopsoas impingement, such as an anteriorly tilted pelvis and/or externally rotated femur. Understanding this complex relationship is difficult from imaging alone and, as such, measuring only cup prominence on a lateral radiograph or a slice of a CT scan may lead to false

positives. Moreover, the use of imaging alone only provides a measurement of the cup prominence at a single point, which may not be where the iliopsoas wraps around the acetabular margin. For instance, measuring cup prominence from a lateral radiograph will be influenced by the angle of the patient relative to the x-ray source and detector. Finally, the use of the simulation allows a surgeon to better visualise the bony anatomy along with the prostheses, which can assist in understanding the extent of the problem, and aid in their decision-making regarding the most appropriate treatment to rectify the problem.

Seventh, although iliopsoas tendonitis is most frequently attributed caused by impingement between the iliopsoas and acetabular cup, it has several other causes, including large diameter femoral heads, excessive changes to leg length or offset, and protruding screws and cement. Despite this, the simulation developed in this dissertation can only detect impingement between the iliopsoas and acetabular cup. As far as the author is aware, there is no literature that assesses the proportions of patients whose iliopsoas tendonitis is attributed to the various known causes. However, evidence for these other causes of iliopsoas tendonitis were found in Chapter 2 and 3, with the observation of 'false negative' patients; specifically, patients who were symptomatic of iliopsoas tendonitis, but did not have any impingement detected by the simulation. Upon further study of these patients, several of these patients' irritation was believed to have been caused by large diameter femoral heads as these patients had monoblock Delta Motion cups with corresponding femoral head sizes of 48mm. It should be noted that, without preoperative imaging, excessive changes to leg length and offset contributing to the irritation could not be ruled out in any cases; however, protruding screws and cement were ruled out as causes of iliopsoas irritation.

As an extra point of discussion, Chapter 2 also highlighted another potential, and under-studied, cause of iliopsoas tendonitis where the iliopsoas functions as an 'anterior stabiliser'. Specifically, the iliopsoas may be over-utilised in extension and activities of daily living, causing irritation.^{128,157,158} Evidence for this cause of iliopsoas tendonitis has been more theoretical in total hip arthroplasty (THA) patients, but it has been investigated in non-THA patients, such as patients with femoral axial malalignment who require de-rotational osteotomies. To provide more detail of this, a case report of a patient has been provided below that contributed to an award-winning poster presentation at the combined Australian Orthopaedic Association (AOA) and New Zealand Orthopaedic Association (NZOA) Annual Scientific Meeting in 2022.

The patient presented with iliopsoas tendonitis after primary THA surgery on their right hip. They underwent a postoperative computed tomography (CT) scan and functional radiographic imaging. From the CT scan, three-dimensional (3D) models of the patient's bony anatomy and prostheses were generated in ScanIP R-2020.09 (Synopsys, California, USA). After landmarking of the joint, it was observed that the patient had a standing cup anteversion of 43° and a standing functional stem anteversion of -16°. Additionally, range of motion analysis was performed on their hip joint in

SolidWorks 2016 (Dassault Systèmes SolidWorks Corporation, MA, USA), which revealed prosthetic impingement at 20° of external rotation. It was hypothesised that a cause of the significant functional femoral retroversion was a compensatory mechanism occurring at the joint whereby the patient was internally rotating to reduce the chance of posterior prosthetic impingement and anterior instability in standing. The low range of motion for the femur in the axial plane indicated that the iliopsoas may have been functioning as an anterior stabiliser to the joint, resulting in overuse and irritation. Preoperative imaging and the 3D reconstructions of the anatomy can be seen in Figure 43.

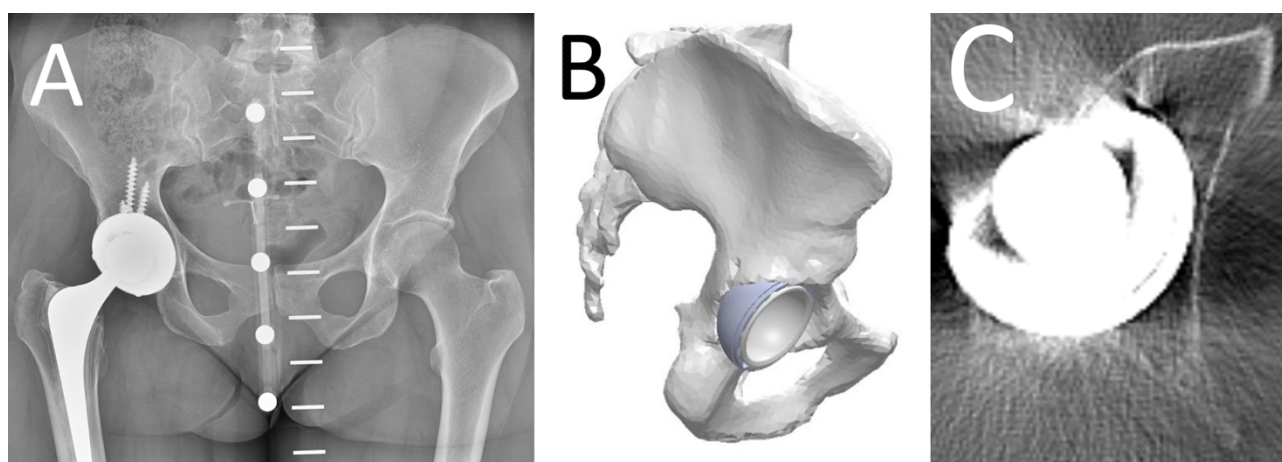


Figure 43 (A) standing anteroposterior (AP) radiograph of patient after primary THA surgery. (B) 3D reconstruction of bony and prosthetic anatomy with significant posterior acetabular cup uncoverage, posteriorisation of COR, and high acetabular anteversion. (D) Axial slice from CT scan to highlight posterior uncoverage.

Revision surgery was indicated by the treating surgeon. Both the acetabular cup and femoral stem were revised to correct the acetabular and femoral anteversion, and to 'de-load' the iliopsoas muscle. The challenges of this revision surgery included low-volume acetabulum and the need for a smaller cup to ensure appropriate axial alignment without anterior overhang to avoid iliopsoas impingement. To achieve stability with a smaller cup, the centre of rotation was medialised and anteriorised from its location. This treatment resulted in complete relief of pain, and can be seen in Figure 44.

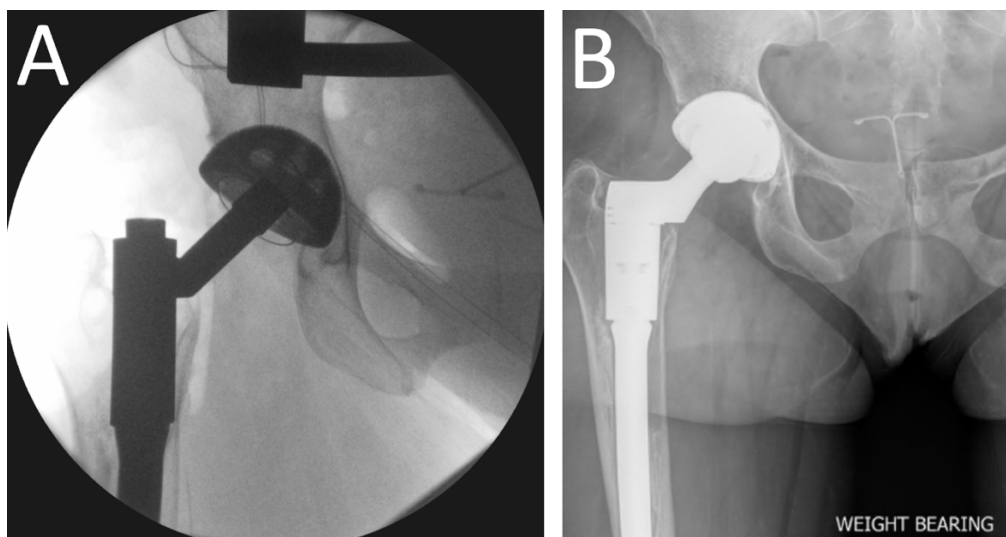


Figure 44 (A) Intraoperative fluoroscope of revision of cup and stem. (B) Postoperative AP pelvic radiograph with revised cup and stem, both with dramatically altered anteversion values to 'de-load iliopsoas.

Further Work

The Relationship Between Iliopsoas Tendonitis and Spino-Pelvo-Femoral Factors

Other than the development and assessment of the iliopsoas impingement detection simulation in THA and HRA patients, one of the key takeaways of this dissertation has been highlighting the potential relevance of spino-pelvic and pelvo-femoral kinematics in iliopsoas tendonitis. There has been some work into the link between iliopsoas-related groin pain and the spino-pelvic construct, such as the studies by Okamoto et al.¹⁷⁷ and Verhaegen et al.¹⁷⁹ However, this area of research warrants further research.

Okamoto et al.¹⁷⁷ performed a retrospective case-control analysis of patients following THA by correlating spino-pelvic parameters measured on radiographs and the psoas muscle index (PMI) with responses to questions about how the patients perceive their joint; whether it feels 'artificial' or 'natural'. Interestingly, the authors observed that indicators of degenerative spinal disease, such as flatback deformity (defined as a greater than 10° difference in pelvic incidence and lumbar lordosis; $PI-LL > 10^\circ$), and a lower PMI were significant predictors of an artificial perception of the hip. However, it was not clear from the study what the sequence of biological mechanisms that lead to patients perceiving their hip artificial was. Specifically, were patients experiencing postoperative iliopsoas-related groin pain that led to less utilization of their iliopsoas muscle, and a subsequent decrease in PMI and increase in spinal degeneration? Or, alternatively, were patients already suffering from a deteriorating spine that led them to develop compensatory mechanisms to reduce the pain, which involved less utilisation of the iliopsoas muscle and a decreased PMI?

Verhaegen et al.¹⁷⁹ performed a retrospective case-control analysis of patients who had undergone anterior approach THA to determine the risk factors for iliopsoas tendonitis. The outcomes assessed included acetabular cup orientation, leg length changes, complication rates, and reoperation rates. The authors had also prospectively collected patient-reported outcomes measures (PROMs), including the Hip Disability and Osteoarthritis Outcome Score (HOOS). The patients who were identified as having iliopsoas tendonitis were younger than patients who did not have iliopsoas tendonitis ($p < 0.001$). Additionally, the authors observed that younger age and the presence of a spine fusion were significant predictors of iliopsoas tendonitis, providing further evidence of the interplay between spino-pelvic and postural factors with iliopsoas tendonitis after THA surgery.

A study to resolve the relevance of spino-pelvic kinematics in the manifestation of iliopsoas tendonitis would be a prospective trial of patients undergoing THA surgery. All patients would need to undergo preoperative planning, including 3D templating of the components, modelling of their iliopsoas tendonitis risk using the simulation developed in this thesis, and measurement of preoperative functional radiographs. Important parameters that would need to be collected or measured preoperatively would include standing pelvic tilt, standing lumbar lordosis and pelvic incidence (permitting categorisation of patients with 'flatback deformity'; $PI-LL > 10^\circ$), PMI, and patient reported outcome measures (PROMs), such as the Forgotten Joint Score (FJS). The FJS may be optimal as it is less prone to the 'ceiling effect' compared to other PROMs,^{206,207} where the ceiling effect is a high frequency of patients achieving the maximum score on a questionnaire, often despite other complaints. Therefore, the FJS, which asks questions about patients' perceptions and experiences of their artificial joint, may be better suited to identifying postoperative soft tissue complications. All patients would need to be followed-up post-surgery at multiple time points, with additional collection of postoperative imaging, such as functional pelvic radiographs and a CT scan. At each follow-up appointment, patients would need to be questioned about postoperative pain, and PROMs would need to be re-collected to investigate how they change over time. The key questions this study might be able to answer are:

- ◇ Which risk factor is most accurate at predicting postoperative groin pain; the iliopsoas impingement detection simulation, spinal malalignment, PMI, or a combination?
- ◇ Are PMI and sagittal spinal deformity independent risk factors, or are they causally linked?
- ◇ What is the relationship between iliopsoas tendonitis, iliopsoas impingement and sagittal spinal malalignment? Specifically, is iliopsoas impingement required in patients with spinal malalignment to develop tendonitis, and the spinal deformity then exacerbates it? Or can iliopsoas tendonitis occur in absence of iliopsoas tendonitis solely due to the spinal malalignment?

- ◇ Is iliopsoas tendonitis exacerbated by a pelvis that rotates posteriorly after surgery? Specifically, does a patient's groin pain worsen over time as their pelvis rotates posteriorly? Is this increase in pain directly associated with greater impingement between the iliopsoas and acetabular cup, or is it related to pain in their back due to spinal malalignment? Are there patients who experience iliopsoas tendonitis years after their hip replacement due to their posterior pelvic rotation passing a threshold value, exposing the acetabular cup to the wrapping path of the iliopsoas?

Integration of the Iliopsoas Simulation into a Preoperative Planning Platform

Prototype development of incorporating the iliopsoas impingement detection simulation into 360 Med Care's preoperative planning platform – 360Hip™ – is underway, which represents a potential translation of the research undertaken in this dissertation into a product that contributes to improving patient outcomes in hip arthroplasty surgeries. So far, this has involved recreating the iliopsoas wrapping path algorithm in C# programming language, and testing the impingement outputs from RStudio and C# in equivalent cases. Interestingly, by integrating the simulation into the live templating platform, the impingement simulation can be run and updated in real-time. For example, a patient can be instantaneously identified as being at high risk of iliopsoas tendonitis in preoperative templating. Then, the acetabular cup can be translated (posteriorly, medially, or superiorly) or the anteversion can be increased, and the simulation can be re-executed for instant feedback as to the patient's updated risk of iliopsoas tendonitis. A screenshot of this can be seen in Figure 45 with the "Risk of Psoas Pain" score on the right hand column that is reflective of the logistic regression curve in Chapter 2 that significantly predicts iliopsoas tendonitis as a function of the maximum impingement between the iliopsoas and acetabular cup. However, for this to become a routine component of 360 Med Care's preoperative planning protocol, further validation would need to be undertaken by simulating the same patients with both C# and R Studio algorithms to ensure same impingement results are observed.

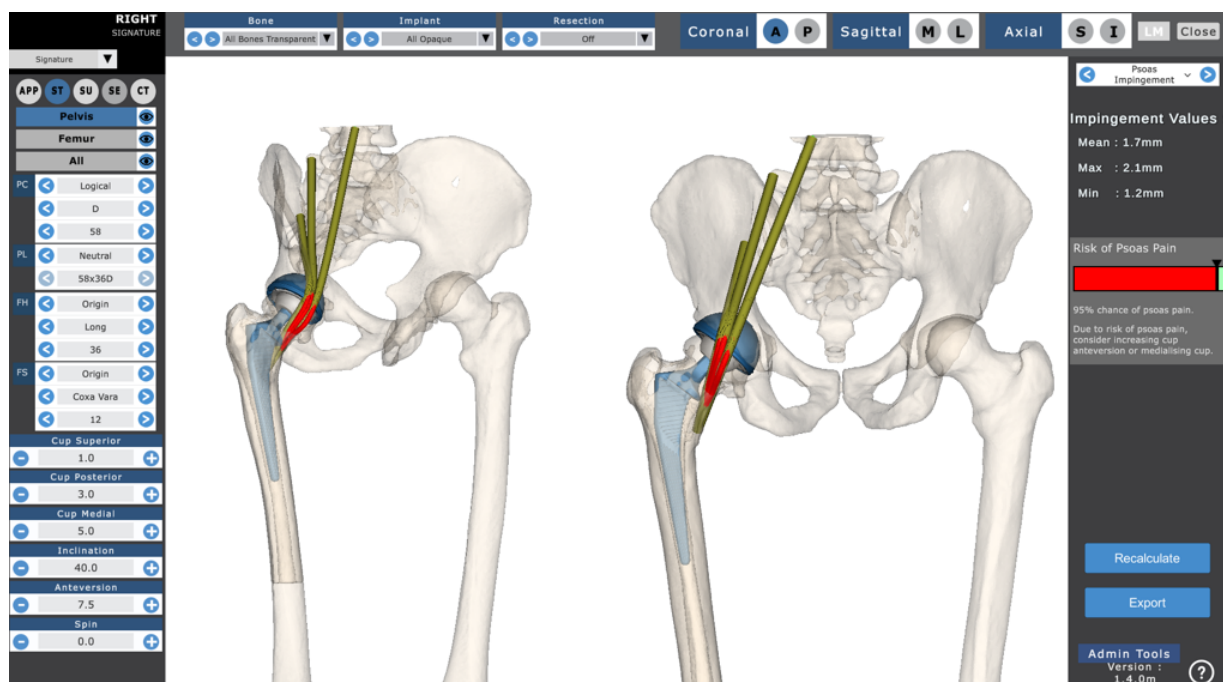


Figure 45 An early prototype of the iliopsoas impingement detection simulation being integrated into 360 Med Care's preoperative planning platform.

Modelling Other Soft Tissue Structures Around the Hip Joint

A similar approach to modelling of the iliopsoas muscle could be applied to other soft tissue muscles around the hip joint. For example, inspired by the work at Imperial College,²⁷ a prototype simulation was developed (Figure 46) that can model the ligaments of the hip capsule and abductor muscles. These ligaments could be simulated in the native state, and then re-simulated after preoperative templating of the implants to assess the change in tension (using length as a proxy for tension) of the ligaments and muscles.

It would be predicted that, due to ligament wrapping around the larger native femoral head, some tension in the ligaments would be lost with the smaller prosthetic femoral head.²⁰⁴ Therefore, to restore the preoperative tension in the joint, vertical or horizontal lengthening would be required, but too much lengthening could be flagged by the simulation. Additionally, thresholds for leg length and offset changes before other soft tissue complications, such as greater trochanteric pain syndrome (GTPS),¹¹² are predicted to occur could be addressed. However, to validate this simulation, additional imaging data would be required that may be difficult to attain, and to justify. Specifically, although the preoperative data would be routinely available, as preoperative CT scans are an essential input to the preoperative planning protocol, the postoperative CT data would not be routinely available.

If this simulation were to be pursued as a way of assessing the degree to which changes in offset and leg length are well tolerated by patients, the author believes studies similar to those

undertaken in Chapter 2 and 3 of this dissertation could be performed. The ideal outcome of this study would be identifying troublesome increases in hip length or offset, which account for the patient's age and gender, that result in abductor or capsular irritation. However, it should be acknowledged that it would be uncertain whether any clinically meaningful results would be derived from this study. Due to this, a preliminary study of preoperative and postoperative AP radiographs, which are more routinely available and require less radiation, may be warranted to determine any correlations between changes to leg length and offset with postoperative soft tissue irritation. Ideally, this would be combined with functional tests and PROMs surveys.

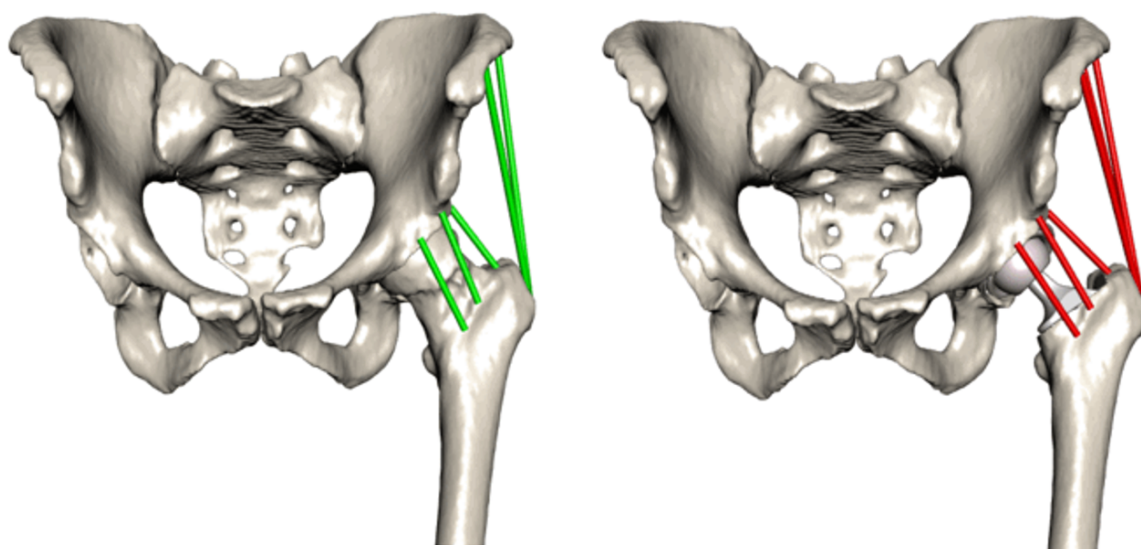


Figure 46 A prototype simulation using the novel approach to representation of soft tissue structures around the hip joint to assess changes in capsular ligaments and abductor muscles from preoperative templating.

Conclusions

In summary, iliopsoas tendonitis remains an under-studied complication of hip arthroplasty. Prior research of iliopsoas tendonitis has typically focused on identifying the incidence of iliopsoas tendonitis or assessing various treatment regimens, and few studies have sought to identify risk factors for the development of postoperative iliopsoas tendonitis.

This dissertation has developed a computational model that can detect impingement between the iliopsoas and acetabular cup, and assessed its accuracy in case-controlled investigations of THA and HRA patients. The simulation uses a novel approach to representing the wrapping path of the iliopsoas by utilising a convex hull to measure the length of the wrapping path with and without the acetabular cup, which permits calculation of the 'stretch' of the iliopsoas (a proxy measurement for impingement) that is due to the acetabular cup. In both studies of THA and HRA patients, the

simulation demonstrated stronger predictive power than cup prominence, which is the standard measurement used to identify iliopsoas impingement.

After validating the simulation, investigations were performed to identify preoperative risk factors that may exacerbate iliopsoas tendonitis; noting that posterior pelvic tilt and a delta between cup size and native femoral head diameter of greater than approximately 6mm were significant risk factors. Irrespective of whether the simulation is used in preoperative planning for hip arthroplasty surgery, these risk factors provide clinically meaningful parameters for surgeons to consider in their pre- and intraoperative workflow.

Each chapter from this dissertation has been published in a peer-reviewed journal, in addition to being presented at engineering and orthopaedics conferences both in Australia and internationally. Research generated from this dissertation has received awards, including an author feature in the Bone and Joint Open (June 2023) and the best poster presentation at the Australian Orthopaedic Association and New Zealand Orthopaedic Association combined Annual Scientific Meeting 2022 for study titled '*Does the iliopsoas act as an anterior stabiliser? A case series investigating a newly proposed source of iliopsoas tendonitis after total hip arthroplasty*'. Further, an Appendix has been included that contains an additional paper that was published by the author in the Bone & Joint Open. This study was undertaken as part of my job in the Research & Development team at 360 Med Care and has been included in the Appendix to demonstrate the breadth of research I undertook whilst completing my dissertation. This study does not have a direct link to iliopsoas tendonitis, which is why it was not included in the body of the dissertation. However, LLD may have consequences for iliopsoas tendonitis, as excessive leg length and offset changes made intraoperatively have been linked to the development of iliopsoas irritation.¹²⁵ Despite this, there is a more general link between this study and the body of my thesis as the study ultimately seeks to contribute to the body of research focused on improving the methods used to preoperatively template and plan for hip arthroplasty, which was an ambition for the iliopsoas impingement detection simulation. Specifically, the LLD study sought to address a significant issue that faces hip arthroplasty surgeons – leg length discrepancy (LLD) – and had two primary aims. First, to assess the inter- and intra-observer reliability of leg length discrepancy (LLD) measurements. Second, to compare the current 'gold standard' measurement LLD on AP radiographs with LLD measurements captured on EOS scans. The results showed found little correlation between the two, suggesting that the AP radiograph is not capturing all sources of LLD, and may not provide an accurate reflection of the patient's true LLD.

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APPENDIX

LEG LENGTH DISCREPANCY ASSESSMENT IN TOTAL HIP ARTHROPLASTY: IS A PELVIC RADIOGRAPH SUFFICIENT?

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Abstract

INTRODUCTION: Leg Length Discrepancy (LLD) is a common pre- and postoperative issue in total hip arthroplasty (THA) patients. The conventional technique for measuring LLD has historically been on a non-weightbearing anteroposterior pelvic radiograph, however, this does not capture many potential sources of LLD. The aim of this study was to determine if long-limb EOS™ radiology can provide a more reproducible and holistic measurement of LLD.

METHODS: 93 patients who underwent a THA received a standardized preoperative EOS scan, AP radiograph, and clinical LLD assessment. Thirteen measurements were taken along both anatomic and functional axes and measured twice by an orthopaedic fellow and surgical planning engineer to calculate intra-operator reproducibility and correlations between measurements.

RESULTS: Strong correlations were observed for all EOS measurements ($r_s > 0.9$). The strongest correlation with AP x-ray (inter-teardrop line) was observed for functional ASIS-to-floor (functional) ($r_s = 0.57$), much weaker than the correlations between EOS measurements. ASIS-to-ankle measurements exhibited a high correlation to other linear measurements and the highest ICC ($r_s = 0.97$). Using ASIS-to-ankle, 33% of patients had an absolute LLD of greater than 10mm, which was statistically different from the inter-teardrop LLD measurement ($p < 0.005$).

DISCUSSION: It was found that the conventional measurement of LLD on AP pelvic radiograph does not correlate well with long leg measurements and may not provide a true appreciation of LLD. ASIS-to-ankle demonstrated improved detection of potential LLD than other EOS and X-ray measurements. Full length, functional imaging modalities may become the new gold standard to measure LLD.

Introduction

Leg Length Discrepancy (LLD) is a common pre- and postoperative issue in total hip arthroplasty (THA) patients. Significant postoperative LLD occurs in up to 32% of patients after THA²⁰⁸ with consequences including dislocation,^{209,210} abnormal gait,²¹¹ sciatica and back pain,^{212–214} patient dissatisfaction,²¹⁵ and litigation.²¹⁶ As acknowledged by Hofman et al.,²¹⁶ the main causes of LLD after THA are insufficient preoperative planning and errors in surgical execution. Despite a wealth of literature on the subject, several key questions remain over which variables to measure and how to best measure them.

Broadly, LLD can be measured two ways: clinically or radiographically.²¹⁷ Clinical measurements include block measurements and tape measurements between anatomical surface landmarks, whereas radiographic measurements include plain radiography and computed tomography (CT).²¹⁷ Studies have compared these two modalities and found radiographic measurements to be no more accurate than clinical measurements.^{218–222}

To further complicate matters, there are also two aetiologies of LLD; a 'true' LLD (tLLD) and an 'apparent' LLD (aLLD).²²³ A tLLD is caused by differences in the actual lengths of bony and soft tissue anatomy, whereas an aLLD is caused by hip/knee contractures or altered mechanics of the spine, leading the patient to perceive a difference in leg lengths while their bony and soft tissue anatomy may be equal lengths.²²⁴ Nakanowatari et al.²²³ found that an aLLD is perceived by almost four times as many patients as tLLD. Similarly, in a sample of 1,114 patients, Wylde et al.²²⁵ demonstrated that 30% reported aLLD, but only 36% of these patients had a tLLD. Additionally, 17% of patients who did not perceive any LLD in fact had a tLLD.

To have a complete understanding of pre- and postoperative LLD, Sabharwal and Kumar²¹⁷ proposed that the ideal measurement for assessing LLD should have three qualities. First, accuracy; the measurement targets what is perceived by the patient (aLLD). Second, precision; the measurement has high repeatability and reproducibility. And third, affordability and availability. However, we propose a fourth quality is needed, granularity; in that the measurement can isolate the specific sources of LLD to understand the limitations of correction from surgery.

A conventional radiographic technique for measuring LLD when planning a THA has been to draw a line through the inferior aspect of the teardrops on a weightbearing (WB) anteroposterior (AP) pelvic radiograph and measure the vertical distance of the most prominent point on each lesser trochanter (LT) to this inter-teardrop line^{226–230} (inter-teardrop to LT). This measurement normalizes pelvic obliquity in favour of determining anatomical differences that exist at the ipsilateral and contralateral hips, such as acetabular cartilage degeneration and femoral head wear. Despite limitations such as internal femoral rotation resulting in difficulty landmarking the lesser trochanter (LT) and magnification error,²³¹ this method is popular. However, it fails to capture other sources of

LLD beyond the pelvis and proximal femur, including scoliosis, flexion contractures at the hip or knee, adduction contractures, anatomical variation in femoral and tibial lengths, and ankle deformities.²¹⁷ An illustration of these sources of LLD can be seen in Figure 47. Hip and knee flexion contractures may cause apparent shortening of the limb, while abduction contractures or equinus deformity of the ankle may lead to an apparent lengthening of the affected hip.²¹⁷ These factors are likely to influence a patient's perception of their LLD and an accurate assessment should include consideration of all of them. In fact, Piyakunmala and Sangkomkamhang²³² found poor agreement between radiographic methods and patient perception. Therefore, it may be said that the pelvic AP radiograph has low accuracy,²³² moderate granularity, and high precision.²²⁸

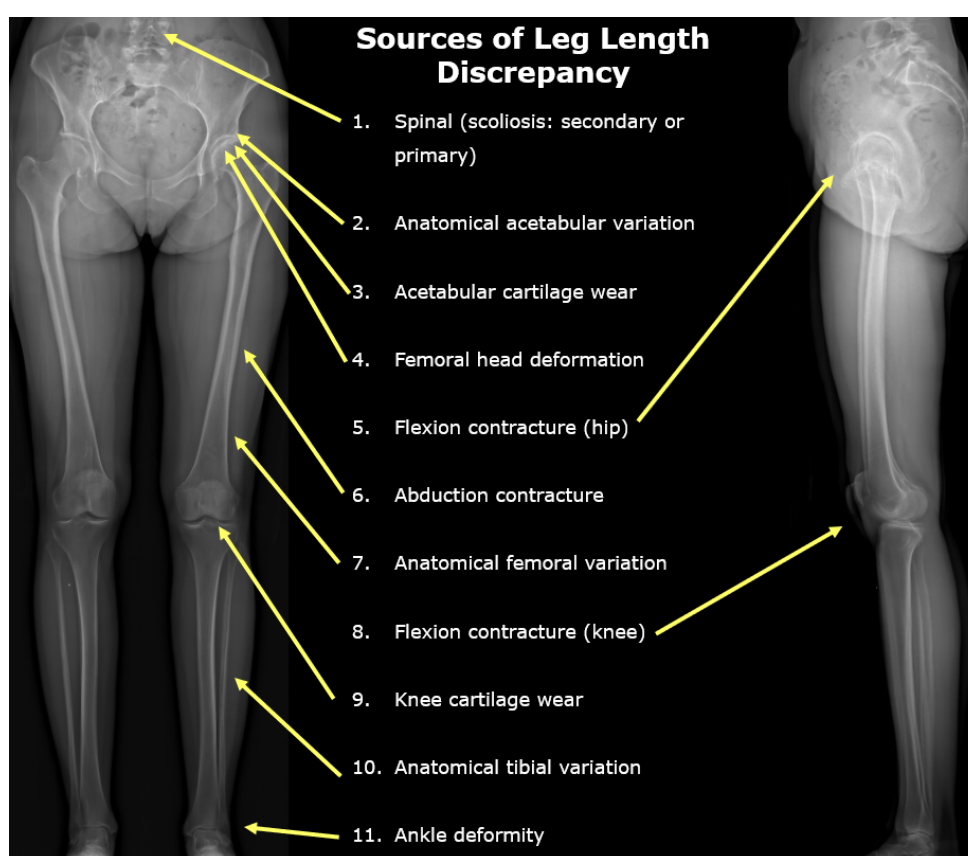


Figure 47 Example long-limb EOSTM imaging to highlight the many different potential sources of leg length discrepancy. Reprinted with permission from the British Editorial Society of Bone & Joint Surgery.

To better capture all the possible sources of LLD, other methods of measuring LLD include long-limb imaging, such as CT scanograms²¹⁷ and, more recently long leg EOS™ scans (EOS Imaging, Paris, France). CT scanograms are taken while the patient is supine and can only be used to determine sources of tLLD, not aLLD. EOS produce simultaneous biplanar images of the subject with very low dose radiation,²³³ no magnification error,²³¹ and allow 3D reconstruction.²³³ This

shows the full-leg functional stance of the patient in the coronal and sagittal planes and captures all potential sources of LLD; both tLLD and aLLD.

As far as the authors are aware, the only previous study to compare LLD measurements from a pelvic radiograph, such as the inter-teardrop to LT measurement, to long-limb measurements was an investigation by Tipton et al.²²². In this study, the authors concluded that LLD measurements on pelvic radiographs were significantly different to a long-limb measurement, and they did not support the use of pelvic radiographs for estimating true LLD. However, this study only investigated one measurement on the long-limb radiography, did not use EOS imaging, which has advantages over plain radiography,^{231,233} and captured the pelvic radiograph measurements by simply zooming in on the long-limb radiograph, which may limit the applicability of its results due to magnification error.

Therefore, the aims of this study were two-fold. First, to assess the relationship between LLD measurements captured on EOS with the inter-teardrop measurement captured from a WB AP X-ray to determine if the WB AP measurement is reflective of the long-limb LLD. Second, to assess the repeatability and reproducibility of all measurements to understand which long-limb measurement may present as the most precise if this imaging modality was adopted. The hypothesis was that long-leg EOS measurements would correlate well with each other, but not with the inter-teardrop measurement on WB AP radiograph.

Patients and Methods

Ninety-three consecutive patients (100 hips) underwent THA surgery from 2 experienced surgeons between July 2020 and August 2021. All patients underwent preoperative surgical planning by 360 Med Care, which included a standardized preoperative EOS scan and WB AP radiograph. Mean age of the patients was 69.6 ± 9.4 and 53% (50) were female. All patients received a Pinnacle (Depuy Synthes) acetabular component and an S-ROM, Corail, or C-Stem (Depuy Synthes) femoral component.

Thirteen measurements were taken, including the inter-teardrop to LT on WB AP radiograph as a reference standard, pelvic obliquity, femoral and tibial lengths, head centre-to-ankle, head centre-to-floor, anterior superior iliac spine (ASIS)-to-ankle, and ASIS-to-floor. A summary of these measurements can be found in Table 16 and Table 17. Measurements were taken along both anatomic (limb aligned) and functional (gravity aligned) axes and on both the operative and contralateral side. Each measurement was measured twice by an orthopaedic fellow and twice by a qualified surgical planning engineer in RadiAnt DICOM Viewer v2.2.5.10715 (Medixant, Poland) with repeat measurements taken at least 2 weeks apart to calculate the correlations between measurements and the repeatability of measurements.

Table 16 Summary of landmarks and axes used for our LLD measurements with their corresponding descriptions.

Landmark or Axis	Type	Definition
Functional Axis	Axis	Measured vertically from the superior landmark to a point level with the inferior landmark
Anatomic Axis	Axis	Measured directly from landmark to landmark
Head Centre	Landmark	Defined by drawing a best-fit circle around the femoral head and taking the centre of the circle
Distal Femur	Landmark	Centre of trochlea groove
Tibial Eminence	Landmark	Junction of eminence (centre of tibial baseplate when a knee replacement is present)
Ankle	Landmark	Cortical border of distal tibia; tibial plafond
ASIS	Landmark	Symmetrical landmarks on anterior iliac crest
Floor	Landmark	The floor; a functional measurement
Adduction	Landmark	Angle between femoral mechanical axis and the vertical axis
Obliquity	Landmark	Angle between Bi-ischial line and the horizontal

Statistical Analysis

Statistical analysis was performed in R Studio v1.3.1903 (Boston, MA, USA). An alpha value of 0.05 was used to determine clinical significance. Shapiro-Wilk normality tests confirmed that not all test parameters were normally distributed. Therefore, Spearman's correlations were used to assess the relationship between measurements. Intra-class correlation coefficient (ICC) was used to assess the repeatability of measurements.

Ethics

This retrospective study was approved by the Bellberry Human Research Ethics Committee (study number 201203710).

Table 17 Summary of all measurements taken on either weightbearing anteroposterior radiograph or EOS.

Measurement	Imaging Modality	Axis
Inter-teardrop to LT	WB AP radiograph	n/a
ASIS-to-Ankle	EOS	Functional
ASIS-to-Ankle	EOS	Anatomic
ASIS-to-Floor	EOS	Functional
Head Centre-to-Ankle	EOS	Functional
Head Centre-to-Ankle	EOS	Anatomic
Head Centre-to-Floor	EOS	Functional
Femur Length	EOS	Functional
Femur Length	EOS	Anatomic
Tibia Length	EOS	Functional
Tibia Length	EOS	Anatomic
Hip Adduction	EOS	(Angular)
Pelvic Obliquity	EOS	(Angular)

Results

Spearman's correlations between all measurements can be found in the correlogram in Figure 48. ASIS and head centre referencing EOS measurements demonstrated the highest correlations with each other ($r_s > 0.9$) and other linear measurements ($r_s > 0.8$). The inter-teardrop measurement had a moderate correlation with ASIS-referencing measurements ($r_s \sim 0.55$) and low correlations with other measurements ($r_s < 0.45$). Pelvic obliquity correlated well with ASIS and head centre referencing measurements ($r_s > 0.8$). Femur and tibia lengths had moderate correlations with other, but low correlations with other EOS measurements ($0.4 < r_s < 0.6$).

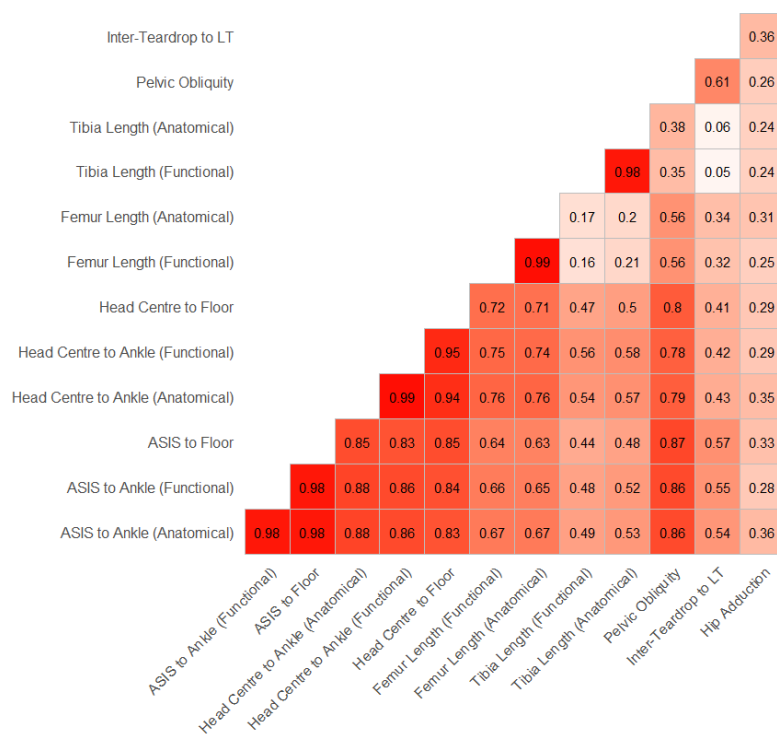


Figure 48 Correlogram showing the linear correlation between all measurements. Reprinted with permission from the British Editorial Society of Bone & Joint Surgery.

The most repeatable measurement was head centre-to-floor, followed by ASIS-to-ankle. However, most measurements had an ICC of > 0.9 and all non-angular measurements had an ICC > 0.8 . ICC values for all measurements can be seen in Figure 49.

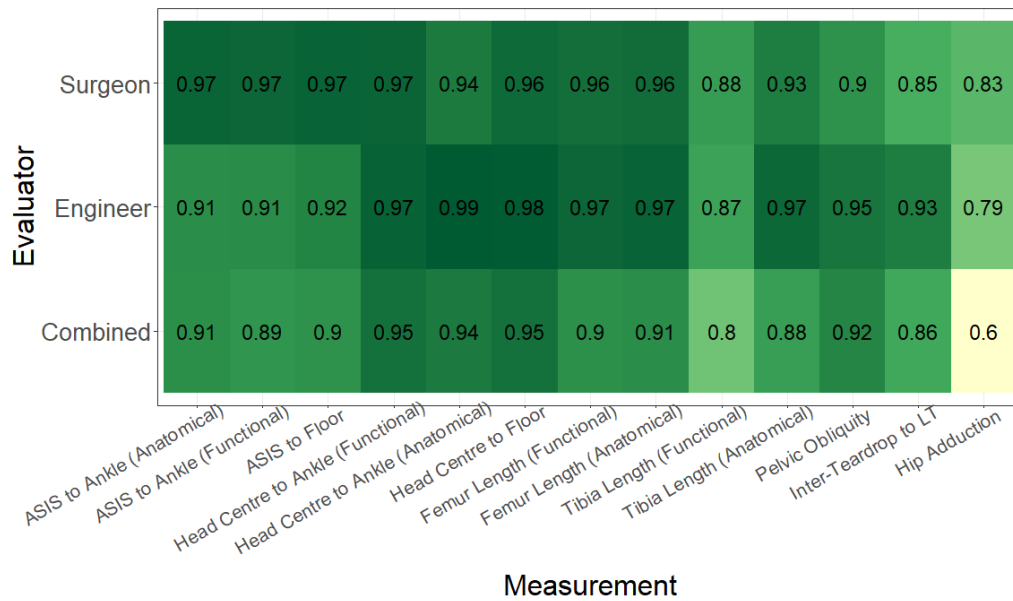


Figure 49 Intra- and Inter-Class Correlation Coefficients of all measurements. Reprinted with permission from the British Editorial Society of Bone & Joint Surgery.

Mean LLD measured on the WB AP radiograph was 1.7mm (± 5.6), and 4.2% patients had an absolute LLD of greater than 10mm. Mean LLD measured using head centre-to-ankle (anatomic axis) was 0.6 (± 8.0) and 17.9% of patients had an absolute LLD of greater than 10mm. Mean LLD measured using ASIS-to-ankle (anatomic axis) was 3.1 (± 12.2) and 32.6% of patients had an absolute LLD of greater than 10mm. The percentage of patients with greater than 10mm LLD measured using these long leg measurements was statistically different from the AP inter-teardrop LLD measurement ($p < 0.005$). A spread of LLDs using different measurements along both anatomic and functional axes can be seen in Figure 50.

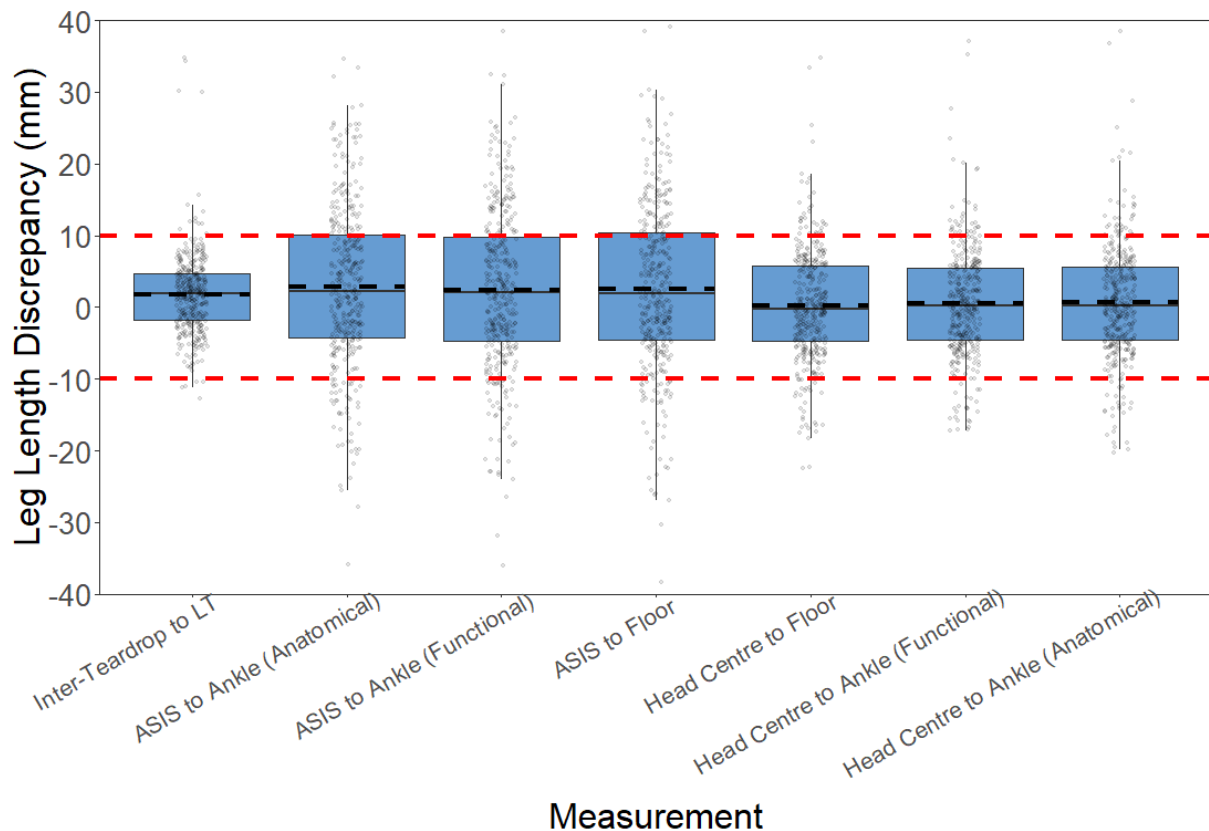


Figure 50 Box and whisker plots to demonstrate the variability of leg length discrepancy measurements when using different landmarks and axes. Reprinted with permission from the British Editorial Society of Bone & Joint Surgery.

Discussion

LLD is a critical consideration in THA as large LLDs may lead to adverse outcomes for the patient.^{209–215} Lack of clarity over the best technique of measuring and addressing LLD has led to this being one of the most widely litigated issues in orthopaedic practice.²¹⁶ Conventionally, clinicians may assess LLD radiologically on a WB AP pelvic radiograph,^{226–230} however, this only captures anatomical sources of LLD at the level of the hip joint.²²⁶ Other methods of measuring LLD include CT scanograms,²²² tape measure,²¹⁷ and block measurements,²¹⁷ but these are subject to various limitations regarding their accuracy, precision, and granularity.^{217,221,227,234}

Therefore, using a consecutive series of patients undergoing THA, this study sought to investigate whether functional EOS imaging might provide a more complete understanding of LLD by addressing the four qualities that a LLD measurement should have; accuracy, precision, affordability and availability, and granularity.

With no correlation coefficient higher than 0.57, it was found that the conventional inter-teardrop to LT measurement of LLD does not correlate well with other long-limb measurements. Reduced inter- and intraobserver agreement were also found for this measurement, indicating limitations in

its repeatability and reproducibility. Therefore, similar to Tipton et al.,²²² Kjellberg et al.,²²⁷ and Sabharwal et al.,²¹⁷ these results call into question the validity of using the WB AP radiograph to measure LLD as they indicate that it does not provide a complete understanding of LLD.

The ASIS-to-ankle measurement in both the functional and anatomic axes was observed to have a high repeatability (ICC > 0.9) and strong correlations with pelvic obliquity and other EOS measurements. This measurement may provide greater detection of clinical LLD than other measurements and, where available, there is a strong case for use of this measurement to determine pre- and postoperative LLD. This is enhanced by the fact that EOS imaging has been shown to not be subject to magnification error, regardless of subject BMI, whereas plan radiography is,²³¹ and is also becoming more widely available. However, it should be noted that there is a potential oversensitivity of the ASIS-to-ankle measurement to sources of LLD that naturally correct postoperatively. For example, intraoperative lengthening in response to a hip contracture that corrects after surgery may lead to excessive lengthening. For this reason, the ASIS-to-ankle measurement may have limitations regarding its granularity and the surgeon may need to determine whether to correct these types of postural sources of preoperative LLD or utilise additional methods.

To further explore the notion of the WB AP radiograph not capturing all sources of LLD, example EOS imaging can be found in Figure 51. This imaging is of a 49-year-old lady requiring THA on her left hip due to secondary osteoarthritis from developmental dysplasia of the hip. As seen on the left in this figure (A), the inter-teardrop line on WB AP radiograph shows a 7.2mm LLD. Conventional planning here would be to correct this LLD by lengthening the operative hip by 7-8mm intraoperatively to yield equal leg lengths. However, with the use of the long-leg functional alignment from EOS imaging (B), it is apparent that the patient has different femoral and tibial lengths. These sources of LLD manifest as the left leg being 3-4mm longer. Therefore, attempting to restore the leg lengths by using the WB AP radiograph alone could lead to an operative leg that is over a centimetre longer postoperatively, which has been associated with poor patient outcomes.^{209–215}

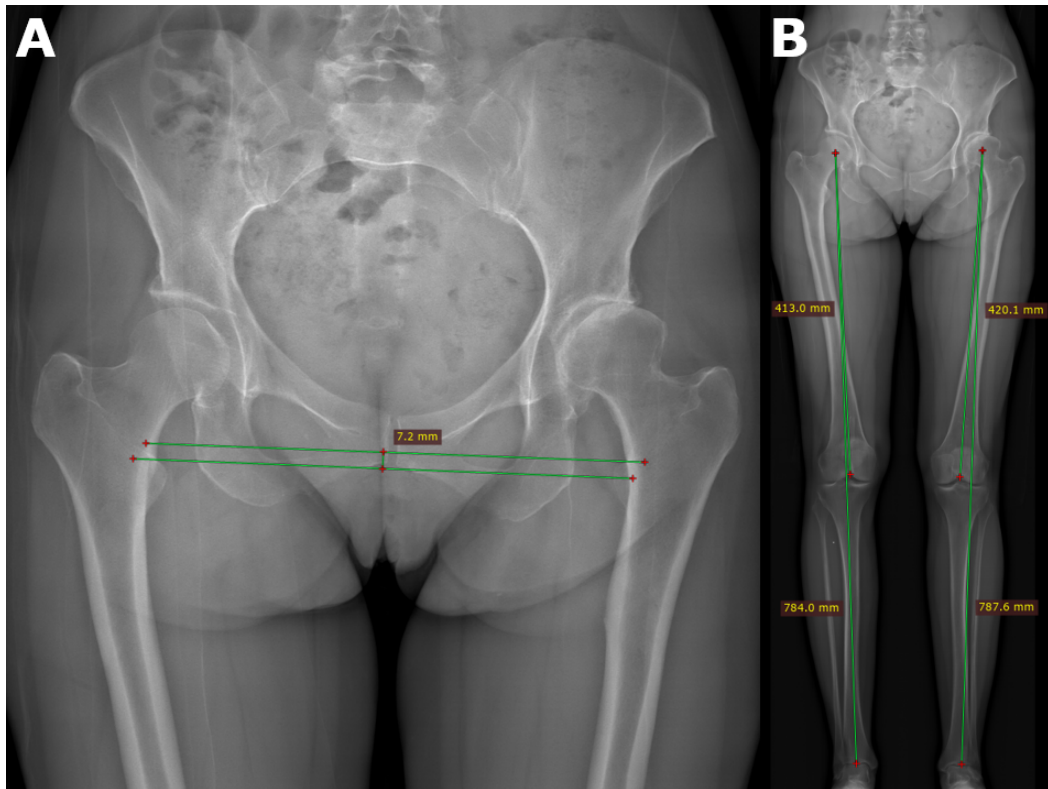


Figure 51 EOS™ imaging from a patient 49-year-old female who underwent total hip arthroplasty. On the left is a zoomed-in recreation of a standing anteroposterior radiograph from the EOS. On the right is the full EOS image of the long leg alignment. Reprinted with permission from the British Editorial Society of Bone & Joint Surgery.

The results of this study should be interpreted within the context of its limitations. First, although EOS has utility in its ability to capture the long-leg functional stance in simultaneous biplanar images, it requires that the subject stand with one-foot forwards and one-foot backwards to ensure the knee joints are not overlapping. This may create an aLLD where one does not exist due to the functional stance of the subject. Second, this study did not include postoperative data, patient reported outcome measures (PROMs), or measurements of the patient's perceived LLD, which would provide insight into the mechanisms of functional correction from pre- to postoperative states and how patients subjectively experience any LLDs that are present. For example, pre- and postoperative data will be required to understand how much a hip contracture corrects postoperatively, and how this subsequently affects any aLLD. Further to this point, although the ASIS-to-ankle measurement has been shown to be precise, this study has not linked this measurement to the patients' experience of LLD as clinical measurements were not included in the assessment. Therefore, its accuracy has not yet been demonstrated. Third, offset measurements, which may also impact the patient's perception of LLD, were not included. Fourth, although EOS imaging machines are becoming more widely available, they are not a standard service at radiology centres. Therefore, the results of this study may not be implementable by all clinicians due to a lack of availability. Future work may investigate maquet view imaging, which is more

widely available, to understand if this better fulfills the four qualities required of LLD measurements. Finally, despite EOS presenting an improvement to previously used methods of radiographically measuring LLD, EOS remains somewhat limited in its granularity for determining which sources of LLD should and should not be corrected from surgery.

In conclusion, the inter-teardrop to LT measurement taken on an AP WB pelvic radiograph, which is widely considered the industry standard for measuring LLD, does not correlate well with measurements taken on EOS imaging. Therefore, there may be a need to reassess the ongoing use of this measurement of LLD. As a replacement, long-limb functional imaging modalities may provide a more complete understanding of all sources of LLD that exist and could become the new 'gold standard' to create postoperatively equal aLLD, which has been proposed as the better target.²²³ Specifically, this study proposes that the ASIS-to-ankle (anatomic) measurement, which exhibited a high correlation to other linear measurements and the highest ICC, may be the best measurement of LLD. Further work should involve the collection of pre- and postoperative EOS imaging, with the addition of patient perceptions of LLD, to understand how contractures correct postoperatively, and to build predictive algorithms that can be integrated into preoperative planning.