Hip Resurfacing Arthroplasty: Investigating the Femoral Component in the Sagittal Plane

by

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A thesis submitted in conformity with the requirements for the degree of Master of Science
Institute of Medical Science
University of Toronto

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Abstract

The outcomes of hip resurfacing arthroplasty are largely dependent on prosthesis positioning. The biomechanics of notching, accurate measurement of femoral implant version and the use of computer navigation of the Birmingham Hip Resurfacing procedure were studied in this work. First, biomechanical tests were conducted with varying notch sizes and femoral positions, and it was determined that anterior notching weakens the construct (p=0.027) when the femur is in flexion and less so when in single-leg stance (p=0.155). Second, three novel techniques were used by three observers to measure the implant version in a lateral radiograph to determine which displayed a more accurate intra-class correlation. The third study examined the role of computer navigation as a learning device for improving the accuracy of femoral implant positioning using a manual alignment jig to curtail sequelae associated with malalignment.
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“Continuous effort – not strength or intelligence – is the key to unlocking our potential.”

-Winston Churchill
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CHAPTER 1
OBJECTIVES

Thesis Objectives

1.1 Thesis Outline

The thesis examines many of the major topics within hip resurfacing to provide the reader with a general understanding of the current concepts of the procedure.

Chapter two begins with an overview of the human anatomy of the hip and an explanation of osteoarthritis, the primary indication for hip arthroplasty, including how it affects the hip. The chapter is concluded with an overview of the history of hip arthroplasty and how the concept of hip resurfacing has evolved into the modern procedure that we use today. Chapter three provides the details of the Birmingham Hip Replacement, describing the surgical technique, current concepts and controversies as well as the basic concepts regarding the mechanical testing of the device in vitro.

Chapters four, five and six each comprise the separate research projects that were completed as a part of the authors Master’s studies. Chapter four is a study exploring the effects of anterior and posterior femoral neck notching on fracture resistance. There lacks extensive biomechanical analysis of this risk factor and will be explored through the mechanical testing of synthetic femurs. The fifth chapter is a study to determine an accurate and repeatable method for the measurement of femoral component alignment in the sagittal plane. The validation of a measurement technique for implant position in a lateral radiograph will allow for future research investigating positioning in this plane. Chapter six is a study investigating the use of imageless computer navigation as a learning device for the placement of the femoral component with a manual jig. This study used the measurement technique established in the prior study for the assessment of implant accuracy.

Chapter seven provides a general discussion on the major topics within the hip resurfacing field and how the findings of this Master’s research contribute to the medical community.

Chapters eight and nine provide a conclusion and a look at future directions for research of hip resurfacing, respectively.
1.2 Aims/Hypothesis

The aim of this work is to advance the methodology of hip resurfacing arthroplasty. By investigating the effects of notching the anterior and posterior cortices, the study aims to reinforce the importance of avoiding femoral neck notching and consequently to influence surgeons’ decisions in the event that a notch occurs during femoral preparation. It was our hypothesis that an anterior femoral neck notch would reduce the overall strength of the construct.

These findings are applicable to those returning to normal activities of daily living and therefore clinically relevant for all patients. Also the assessment of the femoral component alignment in the lateral radiograph is an element of hip resurfacing that has often been overlooked. In order to address the study of femoral component anteversion and its effects on biomechanics, wear, survival or the accuracy of computer navigation, it is imperative to be able to measure a repeatable accurate angle. Chapter 5 provides an articulation and assessment of three such modes of measuring femoral component position in the lateral plane in order to determine the optimal method, with the aim that it can provide a basis for further research in the area of hip resurfacing arthroplasty. Implant malalignment contributes to many of the risk factors that result in early revision of the prosthesis and often occurs during the initial learning period. As a means to improve surgeon learning using the manual jig, we are investigating how training using a computer navigation affects the technical aptitude using the jig. Results from this study may encourage more extensive training with both devices to improve implant positioning.
CHAPTER 2

Introduction

2.1 Overview

The traditional total hip arthroplasty (THA) may be one of the major advances in orthopaedics in the 20th century, but as orthopaedists push the envelope of this procedure to include younger, more active patients, there is also an increased risk of failure. Aseptic loosening of the femoral component is a common reason for revisions of the THA. Revision surgery for aseptic loosening is much more technically demanding and is associated with markedly higher costs and lower success rates. Bone sparing procedures like hip resurfacing can provide pain relief and improved function of the hip joint of the young active patient while maintaining the proximal femoral head, which is extremely beneficial should a revision be necessary. As osteoarthritis in the young adult is becoming more prevalent in today’s population, there may be a growing need for longer lasting hip reconstruction.

In addition to conserving the proximal femoral bone, hip resurfacing offers many additional advantages to patients. As the majority of the proximal femur is preserved and only the femoral head is fitted with a prosthesis, the normal biomechanics of the hip are more closely recreated than with a total hip replacement. There is also the advantage of the metal-on-metal bearing surface. This hard bearing surface allows for the acetabular cup to accommodate a larger femoral head diameter because it does not have the polyethylene liner. The larger head size has been shown to have much lower dislocation rates – a common complication with THA.
Despite these positive attributes of hip resurfacing arthroplasty, there remains the need for research in order to improve the outcomes of the procedure. The most common mode of failure, femoral neck fracture, is often caused as a result of poor femoral component alignment as well as notching of the superior femoral neck. Although the need to avoid notching is well established in the literature and has been commonly accepted in the field, the procedure is quite technically demanding and this is not always possible.\(^4\)

### 2.2 Anatomy of the Hip

The acetabulofemoral joint forms the connection between the lower limb and the pelvic girdle. It is a strong and stable multiaxial enarthrodial or ball-and-socket type of synovial joint. The acetabulum is the cup-shaped socket that is formed by the fusion of the primary bones of the hip – the ilium, ischium, and pubis. The acetabulum has deepened articular anterior, posterior and superior walls that surround the nonarticular acetabular fossa. The acetabulum is directed inferiorly, laterally, and anteriorly in normal human anatomy. This direction allows the weight-bearing iliac portion of the acetabular rim to overlie the femoral head, which is important for the weight transfer to the femur in the standing/walking position. Anatomical changes in the acetabular depth and direction contribute to conditions such as acetabular dysplasia and
retroversion respectively. Both conditions have been shown to contribute to osteoarthritis, the leading indication for hip resurfacing arthroplasty.\textsuperscript{5,6} Several studies have confirmed that acetabular joint reaction forces are directed posteriorly and superiorly when viewed in the sagittal planes.\textsuperscript{7,8} The highest acetabular contact pressures occur in its posterior aspect.\textsuperscript{9} Any deficiency of the posterior wall, due to a malorientation or dysplasia, will therefore result in increased contact stresses, which may contribute to the development of osteoarthritis of the hip.

The femur is the longest and heaviest bone in the body and transmits body weight from the pelvis to the tibia. The femur consists of the shaft (diaphysis) and a proximal and distal end (epiphyses); the transition between diaphysis and epiphyses is the metaphysis. The proximal femur includes the femoral head, which is the ball of the acetabulofemoral joint, the femoral neck, and two trochanters.\textsuperscript{10} The round head of the femur makes up two thirds of a sphere that is covered with articular cartilage, except for a medially placed depression, the fovea for the ligament of the femoral head. The proximal femur is angled so that the axis of the head and neck project superomedially at an angle to that of the obliquely oriented shaft. This obtuse angle of inclination SSA (stem-shaft angle) is greatest at birth and gradually diminishes until the adult angle is reached (115 to 140 degrees, averaging 126 degrees).\textsuperscript{10,11} This gives the proximal femur a unique anatomy that creates mechanical advantages for hip function. As the SSA moves to a less valgus position, this moves the greater trochanter laterally and increases the abductor lever arm, thus increasing the mechanical advantage of the abductor muscles. In the sagittal plane, femoral neck antversion is the normal femoral torsion or twist to the proximal femur and is an average of 8-15 degrees. Femoral antversion can be defined as the angle formed by the femoral condylar plane and a plane passing through the center of the neck and femoral head. This angle is biomechanically advantageous during movement by reducing the horizontal turning moments experienced in the neck of the femur. This has clinical importance in total hip replacement and in the positioning of implants in order to reduce the strain on the bone surrounding the femoral component and hence limiting the potential for loosening.\textsuperscript{12} It also increases the range of movement of the replacement without causing impingement, and therefore enhances stability.\textsuperscript{13}
As the hip is a multi-axial joint, it can perform many types of movements. These movements include flexion-extension, abduction-adduction, medial and lateral rotation, and circumduction. To perform these movements there are many muscles that cross the hip joint and are grouped according to the function that they perform.

Some of the major muscles include iliopsoas, gluteus maximus and a group of muscles collectively known as the hamstrings. The iliopsoas is primarily responsible for hip flexion, and the gluteus maximus is responsible for extension of the leg from the flexed to straight position. Further extension of the leg is achieved by the hamstrings. Some muscles in the hip can perform multiple motions such as the adductor magnus which primarily serves as an adductor but also assists in flexion and extension. Abduction and medial rotation is achieved by the gluteus medius and gluteus minimus as well as the tensor fascia lata.

**Figure 2. Normal hip anatomy.**

2.3 Indications for Surgical Treatment

2.3.1 Osteoarthritis

Osteoarthritis (OA) is the most common joint disease and is commonly seen in the elderly population; however, it is becoming more common at an early age and is no longer considered a normal process of aging, but is now recognized as a multi-factorial process. Osteoarthritis primarily affects articular cartilage, a type of avascular tissue that provides a low friction surface and is able to withstand the forces transferred through the joints. Early in the disease, the loss of cartilage is accompanied by the progressive loss of joint space however the subchondral anatomy is preserved. As the disease progresses the subchondral bone on both sides of the joint may hypertrophy and appear sclerotic. With even further progression of the disease, there is a loss of subchondral bone and eventually progressive bone loss and, in the case of hip OA, this leads to femoral head migration. Also, the femoral neck enlarges and pathophysiologic bone formations called osteophytes form at the joint margins. Large osteophytes are especially common at the acetabular periphery, on the medial acetabular floor and at the superior-anterior femoral neck.

Epidemiology

Osteoarthritis is the most common form of arthritis and a leading cause of disability in the developed world. Osteoarthritis affects 10% of Canada’s population. Although the prevalence of OA is higher in men before age 45, and higher in women after age 55, men and women are equally affected when all ages are considered. The fact that the incidence of OA increases significantly with age has led to the erroneous conclusion that OA is simply an age-related condition. Indeed the prevalence of OA increases with age because of ligamentous laxity, a failure of the periarticular structures such as muscles and proprioceptors to function appropriately, and a reduction in matrix production by chondrocytes. However, other possible risk factors for OA include gender, genetic predisposition, obesity, higher than normal bone mineral density, and joint trauma.

Etiology

Although the exact etiology of primary osteoarthritis is relatively unknown, current evidence indicates several factors are associated with the development of osteoarthritis. Increased age is the strongest risk factor associated with the development of OA. Aging is associated with
changes in cartilage that affect its ability to withstand fatigue forces, changes in joint congruity and changes in peripheral nerve function, all of which may contribute to making cartilage more susceptible to OA. The daily stresses applied to the joints, particularly weight-bearing joints such as the hip, also play an important role in causing osteoarthritis.\textsuperscript{19,20} Other risk factors for OA include: obesity, trauma and genetics.\textsuperscript{18} Osteoarthritis can be divided into two types: primary and secondary. Primary osteoarthritis results from a defect in cartilage’s ability to maintain itself. Secondary osteoarthritis results when cartilage’s ability for homeostasis has been altered by inflammatory, metabolic, structural, or biomechanical factors.\textsuperscript{18} Hip arthritis can result from several different patterns of joint failure. Underlying pathological changes due to conditions such as osteonecrosis, trauma, sepsis, Paget’s disease, and rheumatoid arthritis can produce degeneration of the joint. Conditions such as developmental dysplasia of the hip (DDH) and slipped capital femoral epiphysis (SCFE) leave the patient with predisposing anatomic abnormalities which can later result in osteoarthritic deterioration. When any of these conditions can be identified, the degenerative process is termed secondary osteoarthritis. When neither an anatomic abnormality nor any specific disease process can be identified, the condition is called “primary OA,” which is, therefore, a diagnosis made by exclusion.

As mentioned earlier, anatomical abnormalities can contribute to the progression of osteoarthritis of the hip. There is a close relationship between acetabular retroversion and femoroacetabular impingement (FAI) and the development of osteoarthritis. Acetabular retroversion can be seen in both non-dysplastic and dysplastic hips and refers to the alignment in the sagittal plane. In the normal hip the acetabular opening is anteverted from the sagittal plane. In the retroverted condition the opening, and in particular its proximal rim (the roof edge), lies at an angle of retroversion from this plane. In the case of a retroverted dysplastic acetabulum, the posterior portion of the wall is deficient. A maloriented articular surface with decreased contact area in circumstances such as dysplasia and retroversion of the hip typically leads to excessive and eccentric loading of the anterosuperior portion and subsequently promotes the development of early OA of the hip.\textsuperscript{21,22} There are two types of FAI: cam and pincer. The former occurs because of an abnormal shape of the head-neck junction of the femur; this is also known as a ‘bullet-shaped’ femoral head or slipped upper femoral epiphysis. Pincer type impingement is a result of excessive acetabular cover secondary to a retroverted acetabulum. Both forms may lead to early osteoarthritis of the hip.\textsuperscript{23,24}
Figure 3. AP radiograph comparing the normal anatomy of a left hip to a hip affected by OA (left). Digital representation of the anatomical changes caused by OA (right).

2.4 History of the Hip Resurfacing

2.4.1 Early Generations, variations, successes and failures

The origin of hip resurfacing is generally attributed to Dr. M.N. Smith-Peterson, whose mould arthroplasty was not intended as a hip replacement originally but as a mould for cartilage regeneration. In 1923 a piece of glass was removed from a patient’s back; having been there for a year, it was surrounded by a minimal amount of fibrous tissue and lined by a synovial sac. This discovery gave rise to the thought that a process of biological repair existed which might be applied to arthroplasty. It was believed that a mould of some inert material interposed between the surfaces of the femoral head and acetabulum would guide the repair so that defects would be reduced significantly. Upon completion of the repair, the mould would be removed – leaving a congruous joint surface. Initially, the procedure was attempted using glass moulds; however, these were prone to breakage after being in place for a matter of months and the regenerated surfaces were often incomplete, mainly composed of fibrous cartilage and not optimal for weight
bearing. Over the following years, a number of biomaterials were used as an alternative to glass, including Viscaloid in 1925, Pyrex glass in 1933, Bakelite in 1937 – all without much success. This eventually led to the first metal-on-metal mould hemi arthroplasty made from Vitallium, a cobalt–chromium (Co–Cr) alloy, in 1938. Despite having no means of stable fixation to the femoral head, some survived for many years, although the outcomes were of varied success. Problems relating to cup stability led to the development of the acrylic ‘ball-on-stick’ design by the Judet brothers in 1946. Although this stemmed design addressed the issue of fixation, the implants met similarly negative outcomes with early resurfacing designs, primarily due to osteolytic reaction of surrounding tissue. Shortly after, the first total hip resurfacing prosthesis was introduced by Sir John Charnley in the early 1950s. Charnley’s prosthesis utilized the low frictional properties of Teflon; however, due to its poor wear characteristics, severe osteolysis and Teflon wear debris, the majority of implanted prostheses failed and the use of Teflon was discontinued. Metallurgical and manufacturing limitations of the time severely hindered the metal-on-metal bearing from the outset. Additionally, there continued to be a lack of solid implant fixation at the bone-implant interface, contributing to the failure of many of the first generation components. This became a major focus of future hip resurfacing designs.

Later generations attempted to address the issue of fixation by using cement to achieve rigid internal fixation. During the 1970s the concept of hip resurfacing saw a resurgence due to designers and surgeons’ consensus that fixed cemented implants, with the entire joint mobility located at the interface between femoral and acetabular components, would provide the best pain relief and durability. The Co-Cr cemented femoral head and polyethylene cup design was used simultaneously by Wagner in Germany, and Paltrinieri in Italy, Freeman in the United Kingdom, Gerrard in France, Amstutz in the United States. These implants suffered many of the same problems as the early resurfacing arthroplasties with high revision rates due to femoral neck fracture, osteolysis and implant loosening and subsidence. Consequently, hip resurfacing as a joint replacement therapy was largely abandoned in the 1980s.

2.4.2 Modern Hip Resurfacing Arthroplasty

The current generation of hip resurfacing devices exclusively use a cobalt-chromium-molybdenum alloy (CoCrMo). This new design was introduced by Derek McMinn in the 1990s as a press-fit cementless stemmed femoral head and smooth-backed acetabular cup. Ultimately, McMinn began to modify his components to include a hydroxyapatite coating on macro-sized
beads and a cemented femoral head, leading to the final design which became the Birmingham Hip Resurfacing prosthesis.\textsuperscript{33} In addition to McMinn’s device, Amstutz used the experience from his earlier THARIES (Total Hip Articular Replacement by Internal Eccentric Shells) design to develop the Conserve and Conserve Plus in 1996. With new metallurgical and manufacturing technologies, this third generation of hip resurfacing implants showed greater promise than its earlier counterparts in reducing lysis and wear debris in the joint and ultimately increasing the viability of the joint replacement system. Today, there exist numerous hybrid hip resurfacing systems consisting of a press-fit, cobalt-chrome, porous, hydroxyapatite-backed acetabular component and a cemented, cobalt-chrome femoral component. The most recent reports from series with up to 10 years of follow-up are extremely encouraging and illustrate the importance of instrumentation, patient selection and surgical technique as key elements for the success of resurfacing.\textsuperscript{34-38} Today, the advantages of preservation of proximal femoral bone stock, low dislocation risk and excellent bearing wear characteristics make hip resurfacing an attractive alternative to total hip replacement for the young active patient. However, concerns over the risk of implant failure persist, and there is therefore a need for ongoing research and development for the future improvement of the procedure.
CHAPTER 3
CURRENT CONCEPTS AND CONCERNS

The Birmingham Hip Resurfacing Prosthesis

3.1 Surgical technique

Surgical exposure of the acetabulum is more difficult for hip resurfacing than for standard total hip replacement (THR), as the femoral head and neck are not resected in resurfacing. The other difficulty is that one is often operating on young, muscular men with stiff hips. At St. Michael’s Hospital, a posterolateral approach is used. Once there is an unencumbered view of the acetabulum, sequential reaming with hemispherical acetabular reamers is then performed and in normal consistency bone, reaming proceeds to 1mm less than the specific acetabular component to be inserted. Posteroinferior and antero-inferior osteophytes as well as the acetabular labrum are excised to allow unobstructed cup insertion. The acetabular component is mounted on the acetabular introducer and offered up to the acetabular rim. The acetabular cup is positioned so that its anti-rotation splines are adjacent to the ischium and pubis. The acetabular component is then fully impacted with 15 to 20 degrees of anteversion and 40 to 45 degrees abduction angle. The femoral component positioning is done using imageless navigation – an aspect of hip resurfacing that will be discussed in greater detail in a later chapter. Once the desired guide wire position has been achieved, the guidewire is over drilled to the appropriate depth and the guide wire is replaced with the guide post. The position of the post is then checked using a stylus and the femoral head is de-bulked using the sleeve cutter, taking care not to notch the femoral neck. The femoral head is then marked by cautery for resection to the desired depth by the plane cutter and chamfer cutter. A number of cement keyholes are drilled into the femoral head using the Wroblewski drill and then thoroughly lavaged. Low viscosity antibiotic polymethylmethacrylate (PMMA) bone cement (Stryker Howmedica Osteonics, Allendale, NJ, USA) is mixed and poured into the head implant impacted to the desired position.

3.2 Hip Resurfacing Patient Selection

The ideal candidate for a metal-on-metal hip resurfacing operation is young (55-60) and active and has isolated hip disease with good proximal femoral bone quality and morphology as well as normal kidney function. This type of physiology will allow the patient to resume an active lifestyle once pain relief is achieved by an arthroplasty procedure. Available registry data suggest
that hip resurfacing arthroplasty is a reasonable option for men between fifty-five and sixty years old.\textsuperscript{40}

Table 1. Five-year cumulative percentage revision of primary resurfacing hip and primary conventional THA procedures by gender and age from the AOA Registry. (primary diagnosis osteoarthritis excluding infection)

<table>
<thead>
<tr>
<th>Age (years)</th>
<th>Resurfacing</th>
<th>Conventional THR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Male</td>
<td>Female</td>
</tr>
<tr>
<td>Younger than 55</td>
<td>3.2%</td>
<td>6.1%</td>
</tr>
<tr>
<td>56-64</td>
<td>3.1%</td>
<td>7.4%</td>
</tr>
<tr>
<td>65 or older</td>
<td>5.1%</td>
<td>7.9%</td>
</tr>
</tbody>
</table>

Relative contraindications for hip resurfacing arthroplasty include inflammatory arthritis, severe acetabular dysplasia, poor proximal femoral bone geometry (such as a short femoral neck with a high-riding greater trochanter), poor femoral bone stock due to large femoral head cysts, erosive arthritis, being a woman of child-bearing age, known metal sensitivities, small femoral head, and a limb-length discrepancy of >2cm.\textsuperscript{41,42} Absolute contraindications include osteoporotic proximal femoral bone (such as in elderly patients or those taking corticosteroids long term) because of the increased risks of fracture, compromised renal function due to the risk of impaired excretion of metal ions, and a proximal femoral tumor.

3.3 Complications

3.3.1 Femoral Neck Fracture

Hip resurfacing arthroplasty offers not only the retention of proximal femoral bone but also the improved joint stability and favourable tribology of a metal-on-metal articulation. Although, the preservation of proximal femoral bone stock is desirable, specifically for patients who are likely to require revision surgery in the future, it consequently maintains the risk of femoral neck fracture. In addition to proper patient selection and component design, the avoidance of femoral neck fracture relies on optimal implantation of the prosthesis.\textsuperscript{33,43,44} Hip resurfacing is considered
a technically demanding surgery and the risk of component misalignment is particularly high during the initial learning curve.\textsuperscript{45,46} Despite many advances in surgical technique, femoral neck fractures continue to be the most common reason for revision with an overall revision rate of approximately 1 to 2\% and comprise 43\% of the total number of revisions.\textsuperscript{40,47} The etiology of neck fractures after hip resurfacing are often multifactorial but the most common risk factors are a result of poorly prepared femoral heads in which femoral neck notching, exposed cancellous bone or varus implant alignment has occurred.\textsuperscript{47-50} Adverse radiographic findings that have also been associated with increased risk of femoral component failure include femoral neck thinning\textsuperscript{51} and femoral stem radiolucencies.\textsuperscript{52} Fractures of the resurfacing construct during biomechanical testing occur as a result of both bending and axial compression. The fractures begin in the superior femoral neck adjacent the distal rim of the prosthesis propagating toward the inferior neck in a vertical, shear-like manner and exiting at approximately the level of the lesser trochanter. This transcervical fracture pattern is common in vivo with subcapital fractures. Although most young active patients who receive a hip resurfacing prosthesis are able to return to an active lifestyle, they are often advised to avoid high impact sports in order to reduce the risk of complications.

3.3.2 Femoral Neck Notching

It is often difficult to properly place the femoral component when dealing with the altered anatomy of a patient with osteoarthritis. It is generally recommended that surgeons strive for a relatively valgus placement, however, too much valgus may result in notching.\textsuperscript{49} A notch acts as a stress riser, a location where stress is concentrated. The femoral neck is most resistant to fracture when the strain is evenly distributed over its area, and any concentration of these forces will often lead to fracture.\textsuperscript{53} Notching of the femoral neck may also contribute to neck fractures as a result of damage done to the blood supply to the femoral head.\textsuperscript{54} This disruption of blood supply as a result of notching can also be a cause of late failure via AVN and femoral component loosening. Huiskes found that notching of the femoral neck during hip resurfacing led to a higher rate of femoral component loosening than when no notching occurred: 28.6\% vs 6.8\%, respectively.\textsuperscript{55} This is believed to be the result of osteonecrosis in the resurfaced femoral head that leads to debonding and micromotion at the bone-cement interface, with the subsequent formation of a fibrous membrane and eventual component loosening.\textsuperscript{56}
3.3.3 Exposed Cancellous Bone
While resurfacing has the potential to closely reconstruct the patient’s native anatomy, studies have demonstrated that in doing so, the resurfaced femur may be weakened if unsupported reamed cancellous bone remains exposed. Exposed cancellous bone at the base of the implant occurs as a result of insufficient component lateralization. This may be as a result of attempting to correct a leg-length discrepancy or from inaccurate preparation of the femoral head in which head planing does not extend sufficiently distal coupled with an excessive cement mantle underlying the proximal pole of the implant. Biomechanical evidence has shown that a failure to adequately lateralize the femoral component with exposure of unsupported reamed cancellous bone may weaken the proximal femur by approximately 31%, potentially predisposing it to femoral neck fracture. Insufficient lateralization of the femoral component also increases the bending moment, increasing the stress on the superior femoral neck.

3.3.4 Component Alignment
Implant alignment of both the acetabular and femoral component is integral in the successful outcome of the procedure. Positioning of the components has been shown to be important in improving function and preventing failure following HRA. The orientation of the acetabular
component affects stability, range of movement, and component migration. The positioning of the femoral components in hip resurfacing is also important and influences the incidence of fractures and other complications. When resurfacing regained popularity it was generally perceived that orientation of the acetabular component was not as important as for conventional THR, because the large head virtually eliminated the risk of dislocation. Greater emphasis was then placed on positioning of the femoral component. However, over time it has become apparent that acetabular orientation is more critical with resurfacing than with conventional THR. Steeply inclined acetabular components are more likely to give rise to higher blood metal ion concentrations possibly caused by problems including impingement, edge loading, and lack of fluid film lubrication. To reduce the risk of high blood metal ion concentrations it is suggested that the acetabular component be placed in 40 degrees of inclination and 20 degrees of anteversion. It is often noted that the acetabular wall inclination is approximately 55 degrees, and if the acetabular walls are used to line up the cup edges, the acetabular component will be inserted with much too high of an inclination angle.

With regards to femoral component positioning there is general consensus to avoid varus positioning of the femoral component. By increasing the angle between the femoral shaft and the implant stem, the strains in the superior femoral neck could be reduced. Strain plots of the proximal femur have shown that a valgus orientation of the resurfacing arthroplasty will produce a loading more alike to that of the intact femur; this is of paramount importance in an implant that aims to reproduce physiological loading conditions. Although it is accepted that a valgus placement can improve outcomes, there is no consensus regarding the amount of valgus required. Freeman suggested the femoral component should be placed at as much as 20 degrees to the vertical to align with the medial trabecular system and Amstutz et al. suggested reaming at a 140 degree angle. A recent biomechanical study of paired cadaveric femora suggested improvement in fracture load was achieved with a valgus position of 10 degrees in the specimens with relatively low neck-shaft angles (128 to 132 degrees). This valgus alignment may also provide a protective effect if there is a notch present in the superior femoral neck. There are fewer guidelines with regard to the femoral component alignment in the sagittal plane. However, it is generally understood that the optimal implant placement is in neutral alignment in the femoral neck.
3.3.5 Component Loosening

According to the Australian Orthopaedic Association National Joint Replacement Registry revisions because of component loosening comprised 32% of the total revisions, second only to femoral neck fractures. Aseptic implant loosening can occur as the result of bone degradation and loss surrounding the implant. This loss of supportive bone construct is particularly prominent on the femoral side and may be the result of vascular damage to the femoral head during reaming preparation or stress shielding by the stiff femoral component. The incidence of femoral loosening in most reported series with a 5-year follow-up is low, ranging from 0% to 1.3%. However, these series were for the most part composed of patients with predominately large component sizes and small cystic defects. In a more comprehensive study, a 2% rate of femoral loosening was found in a series with a mean follow-up of 5.6 years. The main risk factors for femoral loosening are small component, femoral head defects larger than 1 cm, and a low body mass index (BMI). The reported incidence of acetabular component loosening is less than 1% for most cementless designs. Surgical technique is key to both the initial and enduring fixation of the acetabular component. The careful assessment of the sphericity and interference fit of the created acetabular cavity are extremely important in achieving initial stability with a monoblock socket where there is no adjunctive fixation system.

3.3.6 Metal Allergy and Hypersensitivity

In recent literature there has been a focus on the effects of increased metal ions as a result of the metal-on-metal bearings of the resurfacing prosthesis. Such concerns are not confined to resurfacing but are also seen with other metal-on-metal hip replacements, and are characterised by aseptic lymphocytic vasculitic associated lesions (ALVAL). There is no consensus for the nomenclature of this entity and it has been referred to in the literature as “metal hypersensitivity reaction”, “pseudotumor”, and “aseptic lymphocyte-dominated vasculitis-associated lesion” (ALVAL). This hypersensitivity response to the metal components composed of cobalt, chromium, molybdenum can contribute to a mass that is neither malignant nor infective in nature; this is what led to it being termed a ‘pseudotumour’. Although the biological mechanisms responsible for pseudotumours are poorly understood, they have distinctive histological features and are characterised by extensive soft-tissue necrosis, macrophages, granulomas and a perivascular lymphocytic infiltrate. They cause a spectrum of clinical
problems, ranging from a small asymptomatic lesion can be detected on a scan to a massive, destructive, infiltrative lesion that causes severe symptoms.

These reactions can vary depending on the materials used. Devices using a low carbon content produce greater wear than bearings made with a high carbon content, whereas the manufacturing process (cast vs wrought) seems to have little effect on the wear of high-carbon components. Diametral clearance has been shown to greatly affect component wear in vitro, particularly with large-size bearings. The diameter of the bearing itself is also an important factor, and larger component sizes have been shown to produce less wear during the bedding in phase because a “continuous fluid film” lubrication mode is more readily achieved with large bearings.

### 3.3.7 Femoral Impingement

Femoroacetabular impingement (FAI) is considered a cause of labral and chondral injuries and a precursor to the development of degenerative hip osteoarthritis (OA) in young adults. FAI is a pathological condition leading to abutment between the proximal femur and the acetabular rim, resulting in damage to the articular cartilage and/or the labrum, as well as limiting range of motion (ROM). As mentioned earlier there are two main forms of FAI: cam-type and pincer-type impingement. The cam-type deformity, also known as the pistol grip deformity when visualized on an AP radiograph, is one of the most common bone abnormalities of the femoral head encountered at the time of resurfacing. The deformity occurs at the junction of the head and neck, resulting in loss of sphericity of the femoral head, a varus tilt, short neck length, and a decrease in anterior femoral head-neck offset. This contour deformity reduces the femoral head-neck offset resulting in decreased joint clearance and early pathological contact with the acetabular rim.
Figure 5. Diagram comparing the three types of femoroacetabular impingement - Cam, Pincer, and Mixed

With repetitive and forceful hip flexion and internal rotation, the aspherical femoral head in cam-type FAI initiates premature avulsion and delamination of the anterosuperior acetabular cartilage.\(^{23,81}\) As a consequence of these pathological changes in anatomy it can become very difficult to place the femoral component and recreate normal offset and geometry. Adequate bone in the femoral head and neck is a prerequisite in ensuring the survival of a surface arthroplasty. The cam deformity can present complications because severe flattening results in segmental bone loss. The superior flattening can predispose to varus malalignment or superior notching. In addition, risk of impingement after hip resurfacing arthroplasty may be greater than in THA since the femoral head-neck unit is preserved.\(^{46,82}\) The prevalence of a cam deformity is reported to be as high as 40% in patients presenting with idiopathic osteoarthritis and occurs predominantly in men.\(^{17,83}\) If this pathological condition remains unrecognized after hip resurfacing, patients could still experience impingement between the femur and the rim of the acetabulum or the acetabular component itself and have a restricted range of motion. Correction of this deformity is also important for component stability, as the experience with metal-on-metal total hip replacements showed early failures due to poor design of the femoral stem, with an inappropriate head-neck offset leading to component loosening and abnormal patterns of wear.\(^{84,85}\) In order to correct for the lack of femoral head offset during hip resurfacing, the component may be required to be positioned further anterior than for a more typical anatomy. In order to accomplish this position without notching the component version is often adjusted to accommodate the femoral neck. For this reason it is important to understand the role of femoral implant version.
3.4 Preoperative Templating

Figure 6. Preoperative templating of acetabular (left) and femoral (right) components

Preoperative templating is an important part of the planning procedure for hip resurfacing as it provides an opportunity to optimally plan the size and position of the resurfacing components in order to avoid significant risk factors for failure. Poor component placement has also been shown to accelerate implant wear and consequently increase blood ion levels in metal-on-metal hip resurfacing. Thus, optimizing implant size and position by way of pre-operative templating may help to improve hip joint kinematics and bearing wear characteristics which may ultimately enhance the longevity of the joint replacement. On the standard AP radiograph of the hip, templating is done to determine the appropriate acetabular cup and femoral component implant sizes. Special attention must be paid to address the templating of the femoral component. The template is positioned over the femoral head, making sure that the implant is in valgus position and not notching on any part of the femoral neck. The stem-shaft angle is then measured. This angle is measured by drawing a line along the anatomic axis of the femur. A second line is then placed from the center of the femoral component to the lateral femoral cortex, typically at the level of the most inferior part of the lesser trochanter.

3.5 Imageless Navigation

One goal of hip resurfacing arthroplasty is to closely reproduce the normal anatomy of the proximal part of the femur and the hip joint, and it has therefore been suggested that implant positioning may have a greater impact on implant survivorship and patient function than it does.
in a conventional hip replacement. Poor preparation of the femoral head is potentially avoidable
and is dependent on proper insertion of the initial femoral guidewire. Commonly, manual
mechanical alignment jigs are used to insert the initial guidewire into the femoral head.
However, these jigs rely on surgeon visualization for guidewire alignment and thus human error
may lead to improper insertion of the guidewire and, ultimately, poor preparation of the femoral
head.\textsuperscript{45,88-90} Computer navigation for hip resurfacing allows the surgeon a means to increase the
accuracy and precision of initial femoral guidewire insertion, while minimizing the likelihood of
femoral head malpreparation.

One of the most important roles for computer assisted surgery is in minimizing the surgeon
learning curve and reducing the incidence of outliers. There is a learning period for imageless
navigation with regards to surgical time. There is a significant improvement in the time taken to
navigate and insert the initial femoral guidewire in the first 20 cases compared to the subsequent
20 cases, with improvements appearing to level off after 60 cases.\textsuperscript{91} However, there is no such
learning curve encountered for implant placement accuracy, suggesting that there may be a
learning curve for the technique of registration but not for the overall accuracy of placement of
the implant. There have been multiple studies demonstrating the use of imageless computer
navigation increasing the accuracy and precision with which the guidewire is inserted in
comparison with conventional jig instrumentation.\textsuperscript{91-95} Imageless navigation also makes it
possible to perform a hip resurfacing on patients with abnormal anatomy that would otherwise
prevent the use of a manual jig. Anatomy such as a severe varus deformity or healed femoral
shaft fracture would make the use of a manual jig extremely challenging. Existing hardware in
situ also presents a challenge when performing resurfacing. Hardware such as AVN rods, blade
plates and DHS’s can occupy the femoral neck and require the precise placement of the femoral
BHR component in order to successfully perform the procedure.
There are also alternative navigation platforms to imageless navigation available to the surgeon. Fluoroscopic navigation provides real-time image guidance, however, image quality, C-arm calibration and radiation exposure remain major limitations to this method. Computed Tomography (CT) based navigation is another image-based navigation method in which a pre-operative computed tomography image is matched to the patient anatomy at the time of surgery. This technique is very accurate as it provides a 3D image for planning and navigation purposes but cost and additional radiation exposure are limits to its efficacy.

3.5.1 Navigation Technique

The intra-operative surgical planning and insertion of the initial guidewire is guided by the Vector Vision imageless navigation system version 2.0 (BrainLAB, Heimstetten, Germany). The system uses anatomical landmarks and surface data to generate a model upon which intra-operative planning can be conducted. It uses two cameras which transmit and receive reflected infrared light to triangulate the position of two optical arrays, a static array and a dynamic pointer. Each array is fixed with three reflective spheres. A 5mm Schanz pin is first drilled into the lesser trochanter and is used to anchor the static array. Next, points at the medial and lateral femoral condyles and the piriformis fossa are acquired and used to delineate the diaphyseal axis.

Figure 7. Navigated hip resurfacing of a femur with hardware in place
Figure 8. Imageless navigation planning screen (left) and verification screen (right)

The superior head-neck junction point is acquired along with clouds of points on the femoral head and the anterior, superior, posterior and inferior quadrants of the femoral neck. Lastly, the anterosuperior part of the neck, the zone for superior notching is registered and provides enhanced visualisation of this critical area. The system calculates the neck-shaft angle, or the caput-collum-diaphysis angle, by fitting a plane to the superior and inferior clouds of points and calculating a mid-plane between the two. The inclination of the mid-plane to the diaphyseal axis is the computed neck-shaft angle. The system also uses the registered data to determine the initial computed size and location of the implant. A computer-generated, patient-specific model is then created and verified for accuracy. An intra-operative planning screen is used to adjust the size, location and angulation of the implant before insertion of the guidewire. A navigated drill guide is used to drill a 2.4mm guidewire into the femoral head. The drill guide provides real-time feedback of the position of the guidewire during drilling. The final location of the guidewire is verified using the same drill guide. The navigation time for the procedure is defined as the time between drilling the Schanz pin into the lesser trochanter and verification of the final position of the guidewire. After verification, a stylus is inserted over the guidewire to check for notching and sufficient resection of the head, and the remainder of the standard protocol for the BHR is then followed for preparation of the femoral head.
3.6 Biomechanics

3.6.1 Basic Biomechanics of the Hip

When investigating the biomechanics of the femur, forces and moments can be applied in various directions, producing many different loading modes. The primary loading modes that occur in the femoral neck are tension, compression, bending and torsion.\(^{53}\)

The two main concepts when examining the strength of material and transmission of force are engineering stress and strain. Stress is defined as the force per unit of cross-sectional area. In the mechanical testing machine, the femurs are subject to either pulling (tensile) forces or pushing (compressive) forces. The units of stress are measured in Newtons per millimeter squared (N/mm\(^2\)). Strain is defined as the increase in length as a fraction of the original length.\(^{53}\) A standard stress/strain curve can be plotted and multiple material properties of the specimen can be calculated. A representative stress-strain diagram for a ductile material is shown in Figure 9. The principles of engineering stress and strain do not take into account the change in cross-sectional area or length whereas true stress and true strain account for highly localized changes in geometry. The engineering definitions are most often used in place of the true stress and strain in the biomechanical study of bone because of the difficulties in gauging the change in cross-sectional area and length while testing.
Several features of the stress-strain diagram in Figure 9 are important and define the mechanical properties of the material being tested. These features are the linear elastic region, yield point, plastic region, ultimate strength, and failure.

**Linear Elastic Region**

In the linear region of the stress-strain diagram, the test piece behaves as a simple spring. When the stress is increased, the strain increases proportionally. If the same amount of stress is let off, the strain decreases to the previous length. No permanent deformation of the test piece occurs. The strain may be altered any number of times with the same results. The forces that occur during the activities of daily life would fall in this range. The slope of the linear region equals the modulus of elasticity (or Young’s modulus) of the material. On the stress-strain curve, stiffer materials have greater slope on the linear portion of the curve.

**Yield Point**
The yield point is the stress at which there is a change from elastic to plastic deformation. Graphically, on the stress-strain curve, the yield point occurs at the transition of a straight line with constant slope to a curved line of variable slope. On the stress-strain diagram, the yield point is not always visually apparent as it is in Figure 9. Consequently, a stress resulting in a 0.2% change in strain is conventionally chosen as the numerical definition of the yield point.

*Plastic Region*

In the plastic region, when the stress is increased the strain increases in a more complex way than it does in the elastic region. The stress-strain curve may decrease for a small interval or it may continue to increase but at a lower or more variable rate relative to that in the linear elastic region. The essential feature of plastic deformation is that it is not completely reversible. If the stress is let off, the test piece will not return to its original geometry.

*Strength*

The ultimate strength is the maximum stress that a material can withstand before impending failure. The yield strength is the strength at the end of linear elastic behaviour and at the onset of plastic deformation. The ultimate strength is the stress at the apex of the stress-strain curve. This is the strength at the end of the plastic deformation portion of the curve if it is higher than the yield point. (See Figure 9 for graphical illustrations.) Failure strength is defined as the point of fracture, beyond the linear elastic region and after plastic deformation. In principle, one can measure the strength at the failure or fracture point. In practice, there is rarely a distinction between the ultimate strength and the strength at failure. Therefore, the ultimate strength is often reported as the final strength measurement of a material.

*Failure*

Failure occurs when the test piece or material fractures and numerous modes of failure are possible. Ductile materials have a process of impending failure that occurs immediately after the stress surpasses the material’s ultimate strength. This is representative to the failure properties of bone as it exhibits both linear elastic and plastic properties. Brittle materials are the opposite of ductile materials. Very brittle materials, such as some ceramics, fail in the linear elastic region, or after a very small amount of plastic deformation.
3.6.2 Mechanical Properties

*Modulus of Elasticity*

The modulus of elasticity is defined as the stress per unit strain in the linear elastic testing of a material and is used as a measure of stiffness of a material. In terms of the stress-strain diagram, the modulus of elasticity is the slope of the stress-strain curve in the range of linear proportionality of stress to strain. For testing bone, the modulus of elasticity characterizes the how the bone will ultimately fracture. The higher the elasticity modulus, the higher stress is needed to achieve bone deformation.

3.6.3 Biomechanical testing

Clinicians and engineers have long been interested in assessing the mechanical properties of human whole bones and implant devices to address a vast array of orthopaedic pathological conditions and traumatic injury patterns. To this end, experimental methods and computational techniques have been employed over the years, separately and in combination.

Mechanical in vitro tests on human cadaveric longbones and/or longbone-implant constructs have been done for over a century.\(^96\) Physiologic loading is a complex interplay of anatomical geometry, material properties, muscle activity, and surrounding soft tissue. Because of the challenges in using cadaveric bone and living subjects, synthetic bone analogs have become an attractive option. Major advantages include no special storage requirements, low cost, commercial availability, no degeneration over time, standardized geometry, and predetermined material properties.\(^97\) These surrogates have been validated against human bones with good results for axial, torsional, and four-point bending stiffness, as well as for cortical and cancellous screw pullout strength. Large, left, fourth generation composite femurs (Model 3406, Pacific Research Laboratory, Vashon, WA, USA) were used for the biomechanical study of notching.

3.6.4 Material Properties of Bone

Bone tissue is a specialized connective tissue with a solid composition for its supportive and protective roles. Similar to other connective tissue, bone consists of an organic extracellular matrix of fibers and ground substance produced by the cells. Biomechanically, bone tissue may be regarded as a two-phase (biphasic) composite material, with the mineral as one phase and the collagen and ground substance as the other.\(^53\) The distinguishing feature of bone is its high
content of inorganic materials, in the form of mineral salts that combine with the organic matrix. The inorganic component of bone makes the tissue hard and rigid, while the organic component allows for flexibility. The composition of bone is dependent on the area of the bone, age, dietary history, and the presence of disease.\textsuperscript{98,99}

The femur consists of cortical and cancellous bones. The cortical bone is high in strength and modulus of elasticity, thus keeping the bone structure in place. In comparison, the cancellous bone is low in both strength and modulus of elasticity. The cancellous bone is also much lower in density due to its sponge-like structure. Since the femurs are usually loaded longitudinally during everyday activities, the combination of the strong cortical bone in the longitudinal direction and the cancellous bone working as a shock absorber allows the body to carry its weight as well as greater loads produced from aggressive activities such as jumping and running.

Bones have anisotropic material properties; they behave differently depending on the orientation of the load. In the case of the femur, the anisotropic characteristics are accentuated by its cylindrical shape.\textsuperscript{100} As shown in Table 2, the femoral shaft has much greater strength in the longitudinal direction than the transverse direction. For example, the ultimate compressive strength is approximately 6 times greater in the longitudinal direction than in the transverse direction (Table 2). The femur can also handle about 31% higher compressive loads in the longitudinal direction compared to tensile loads. However, the femur is weaker in transverse compression compared to transverse tension.\textsuperscript{100} This means that the femur will endure high longitudinal compressive loads but is weak when subjected to transverse loading.
Table 2. Mean values of material properties of the human femur\textsuperscript{100,101}

<table>
<thead>
<tr>
<th>Type of Bone</th>
<th>Direction and Load Type</th>
<th>Density (g/cm\textsuperscript{3})</th>
<th>Ultimate Strength (MPa)</th>
<th>Modulus of Elasticity (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cortical</td>
<td>Longitudinal Tension</td>
<td>1.85</td>
<td>133</td>
<td>17.7</td>
</tr>
<tr>
<td></td>
<td>Longitudinal Compression</td>
<td>1.85</td>
<td>193</td>
<td>17.7</td>
</tr>
<tr>
<td></td>
<td>Longitudinal Shear</td>
<td>1.85</td>
<td>68</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Transverse Tension</td>
<td>1.85</td>
<td>51</td>
<td>12.8</td>
</tr>
<tr>
<td></td>
<td>Transverse Compression</td>
<td>1.85</td>
<td>33</td>
<td>12.8</td>
</tr>
<tr>
<td>Cancellous</td>
<td>Compression</td>
<td>0.31</td>
<td>6</td>
<td>0.76</td>
</tr>
</tbody>
</table>

3.7 Imaging the Hip

3.7.1 Standard Imaging Protocol

Despite the many advances in imaging technology, conventional radiography continues to be the foundation for orthopaedic examinations. Proper selection of equipment and radiographic technique are crucial to obtaining high-quality diagnostic images.

A good quality AP radiograph of the pelvis and AP and lateral radiographs of the affected hip should be ordered as part of the initial evaluation. The radiographs should be examined for evidence of arthritis, fracture, osteonecrosis, and other morphologic abnormalities that could account for the patient’s symptoms. Not all patients with osteoarthritis of the hip are appropriate for resurfacing as the native anatomy may be too small or large and unable to accommodate a resurfacing prosthesis; there may also be the presence of large cysts in the femoral head. Templating using digital radiographs can assist in determining if a patient’s anatomy is suitable for hip resurfacing.

Once the hip resurfacing procedure is completed post-operative images are ordered to confirm the placement of the components. Regular follow-up imaging is important in assessing the status of the implants and allows the surgeon to identify risk factors or changes in anatomy such as, implant stability, and femoral neck narrowing.
Each view is important for the assessment of the prosthesis. The AP view allows the observer to calculate the SSA of the femoral component and examine for a notched femoral neck, both of which are crucial to the outcomes of the procedure. In addition, the AP view shows the abduction angle alignment of the acetabular component and whether it is fully seated. The cross-table lateral is a standard method commonly used for imaging the lateral hip radiographs as it provides a clear view of both the anterior and posterior cortices. Good quality cross-table lateral radiographs allow not only good visualization of both cortices, but show much of the femoral neck and reveal only a small amount of the lesser trochanter – thereby precluding the greater trochanter from obstructing the view of the femoral neck. There are some technical limitations of obtaining a correct and repeatable projection with all radiographs particularly when the range of movement of the patient is restricted due to OA or postoperative surgical wounds. For this reason, the cross-table lateral is used more commonly in a clinical setting because of its simplicity in a clinical setting.

Because the femoral head/neck junction is preserved in hip resurfacing, patients may be at risk of impingement, leading to abnormal wear patterns and pain. The lateral x-ray is an important diagnostic tool for the assessment of femoral anatomy in the sagittal plane, particularly with the assessment of FAI. Most hips undergoing resurfacing have an abnormal femoral head/neck offset, which is assessed in the sagittal plane. On a cross-table lateral the femoral head/neck offset is also measured as a ratio of the anterior offset and the diameter of the femoral head as seen in Figure 10.

Figure 10. Cross-table lateral radiograph of a left synthetic femur
CHAPTER 4
FEMORAL NECK NOTCHING

Chapter four includes a paper exploring how a femoral neck notch on the anterior or posterior femoral neck affects the strength of the proximal femur. Most studies identifying fracture risks, do so through retrospective clinical reviews and there remains limited biomechanical research studying notching of the anterior and posterior femoral neck and is often overlooked. The basis for investigating this effect is that hip resurfacing patients will likely be more active than a typical total hip replacement patient, as they are typically much younger. High out-of-plane forces are seen during many activities of daily living and also in many sporting activities. These forces in combination with a risk factor such as a femoral neck notch could have unfavorable clinical outcomes.

A Biomechanical Investigation into the Effect of Anterior and Posterior Notching on Femoral Neck Fractures Following Hip Resurfacing Arthroplasty

4.1 Abstract
This purpose of this study was to determine the degree to which an anterior or posterior femoral neck notch affects the strength of the hip resurfacing construct.

Forty-seven 4th generation synthetic femurs were implanted with Birmingham Hip Resurfacing prostheses (Smith and Nephew Inc., Tennessee, USA). Implant preparation was performed using imageless computer navigation (VectorVision SR, BrainLAB, Feldkirchen, Germany). The femurs were fixed in a single-leg stance, flexion or extension and tested with axial compression using a mechanical testing machine (Instron, Ohio, USA). The synthetic femurs were prepared in 8 experimental groups: 2mm and 5mm anterior notches, 2mm and 5mm posterior notches, neutral alignment with no notching (control), 5mm superior notch, 5mm anterior notch tested with the femur in 25 degrees flexion and 5mm posterior notch tested with the femur in 25 degrees extension

Superior notching significantly decreased the load-to-failure (2423 N, p=0.001). Both the anterior 5mm notch group in flexion (3048 N, p=0.027) and the posterior 5 mm notch group in
extension (3105 N, p=0.038) displayed significantly lower compressive load-to-failure values than the axially tested controls (4539 N). There were no significant differences between axially loaded femurs prepared with anterior or posterior neck notches (3375-4208 N) and the control group (p≥0.155).

Anterior or posterior neck notching does not appear to affect proximal femoral strength in axial loading but does significantly weaken the resurfacing construct when the femur is in flexion or extension.

4.2 Introduction

Hip resurfacing arthroplasty is increasingly being used as a treatment option for end stage osteoarthritis and is becoming a viable alternative to total hip arthroplasty for active young patients. This growth in popularity is in part due to excellent early and medium term outcomes reported with the new generation of hip resurfacing prostheses.¹⁻⁶ Despite these positive outcomes, however, there are still considerable risks that may lead to implant failure, including femoral component misalignment and femoral neck notching.⁷⁻⁹ It is thus important to investigate these risks in order to assess their impact on implant outcomes. Although there has been significant research carried out on the effects of femoral component alignment and femoral neck notching in the coronal plane, there is a paucity of information investigating the effects of these two risks in the sagittal plane. Therefore, this study aimed to determine the significance of anterior and posterior neck notching on femoral neck fractures following hip resurfacing.

4.3 Methods

To explore the effects of anterior and posterior notching on femoral neck fracture we used ⁴ᵗʰ generation composite femurs (Pacific Research Laboratories Inc., Vashon, Washington). The use of composite femurs reduces the specimen variability otherwise seen in cadaveric testing, and also allowed for larger sample sizes as the availability of cadaveric tissue is often limited. Further, using composite femurs in biomechanical testing has been well validated in peer-reviewed literature.¹⁰,¹¹ Forty-seven large left femurs with a native neck shaft angle (NSA) of 120 degrees and a cellular matrix cancellous bone (model 3406, Pacific Research Laboratories Inc.) were used throughout this investigation. Each composite femur was stiffness tested prior to any preparation of the femoral head to gather baseline data and ensure specimen uniformity.
The composite femurs were randomly divided into eight groups of six femurs each: seven experimental groups and one control group. We consider this to be an adequate sample size; it is equal to the one used in similar studies investigating the structural properties of composite femurs.\textsuperscript{10,12} The experimental groups are as follows:

**Table 3. Experimental groups for biomechanical testing**

<table>
<thead>
<tr>
<th>Notch Group</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anterior Notch</td>
<td>2 mm</td>
</tr>
<tr>
<td></td>
<td>5 mm</td>
</tr>
<tr>
<td>Posterior Notch</td>
<td>2 mm</td>
</tr>
<tr>
<td></td>
<td>5 mm</td>
</tr>
<tr>
<td>Superior Notch</td>
<td>5 mm</td>
</tr>
<tr>
<td>Neutral (control – single-leg stance and flexion)</td>
<td>5 mm</td>
</tr>
<tr>
<td>Anterior Notch in flexion</td>
<td>5 mm</td>
</tr>
<tr>
<td>Posterior Notch in extension</td>
<td>5 mm</td>
</tr>
</tbody>
</table>

All of the femurs were prepared using imageless computer navigation (VectorVision SR, BrainLAB, Feldkirchen, Germany) to ensure accurate implant placement. Specimens were individually registered and digitally mapped using the BrainLAB infrared camera and array system in order to plan the alignment and entry point of the guide wire. This wire provided the basis for the remainder of the standard preparation of the femoral head, including post insertion, central canal drilling, cylindrical reaming, planing and chamfering. To create a notch on the anterior or posterior neck, the implant position was planned in a posteriorly or anteriorly translated position, respectively. The notch depth was then measured by Vernier calipers to be within ± 1mm from the planned notch size. All implants were prepared with a neutral stem-shaft angle (SSA) of 120 degrees. To ensure correct alignment, all stem-shaft angles were verified to be within ± 1 degree by plain digital radiographs. No fractures were visible upon radiographic examination.

Once prepared, the femurs were implanted with the Birmingham Hip Resurfacing (BHR) component (Smith and Nephew Inc., Memphis, Tennessee) using antibiotic cement (Stryker
Howmedica Osteonics, Allendale, New Jersey). Femoral component implant size was determined to be 46mm by gauging the femoral neck using the standard BHR sizing instrument.

The femurs were then positioned with approximately seven degrees of adduction and aligned vertically in the sagittal plane to simulate the loading in single-leg stance. All specimens were fixed in single-leg stance with the exception of two experimental groups. These exceptions have the femur positioned in either 25 degrees of flexion, a loading condition experienced during stair climbing, or 25 degrees of extension to represent an extreme loading condition during a lunge.\textsuperscript{13,14} The resurfaced specimen was then fixed by threaded pins surrounding the distal femur in a stainless steel jig and stiffness tested in axial compression prior to being tested to failure. The vertical load was applied using an Instron 8874 mechanical testing machine (Inston, Canton, Ohio) to a maximum displacement of 0.5mm at a rate of 10mm per minute and with a preloaded force of 100N. Loading in axial compression was chosen as it is the dominant loading force experienced by the femoral neck during gait.\textsuperscript{13}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure11.png}
\caption{Testing set up for femur in single-leg stance (Left), femur in 25 degrees on flexion (Right)}
\end{figure}
Following the stiffness testing of each resurfaced femur, the specimen underwent load-to-failure testing. With the femur correctly positioned the load-to-failure values were determined by applying a vertical force at the rate of 10mm/min until a fracture occurred.

4.3.1 Statistical Analysis
Statistical analysis was performed using the statistical software package SPSS 16 (SPSS Inc., Chicago, Illinois). A paired t-test was used to compare differences between the pre- and post implant stiffness of each femur. A one-way analysis of variance (ANOVA) with Tukey’s post hoc analysis was carried out to compare the difference in post-implant stiffness and load-to-failure between each experimental group and the control. A p-value of 0.05 was considered significant.

4.4 Results

Stiffness testing
A paired t-test comparing pre-implant stiffness values with post-implant values for each experimental group showed a statistically significant increase in stiffness between the intact specimens of the control group: 1486.8 N/mm; SD 150.5 with the BHR implanted neutrally in the neck and devoid of notching 1739.5 N/mm; SD 281.3N; (p=0.011). This was the only experimental group to show a statistically significant change in stiffness values from pre-implant to post-implant as all other p-values were greater than p≥0.07. The presence of a BHR prosthesis implanted in a synthetic bone without a notched femoral neck increased the stiffness of the construct and may have contributed to the strength of the proximal femur during the load-to-failure tests. Analysis of all post-implant groups showed there were no significant differences in stiffness values between any of the experimental groups (p≥0.175).

The two experimental groups with the femur positioned in either 25 degrees of flexion or extension displayed a much lower mean stiffness than those tested in single-leg stance, 695.5 N/mm and 575.21 N/mm respectfully. Analysis of these results showed no statistical difference from the pre-implant stiffness values. The lower stiffness values seen in flexion and extension can be attributed to increased bending along the diaphysis. Furthermore, the high average linearity coefficient ($R^2$) of the force-deflection curve used to determine the stiffness of the pre-implant ($R^2 \geq 0.98$) and post-implant value ($R^2 \geq 0.98$) indicate that the specimens remained within the elastic range and did not incur any damage prior to the load-to-failure testing.
Load-to-failure of specimens in single-leg stance:
Specimens in the superior notch experimental group fractured at a mean load value of 2423.1 N; SD 424.2, a significantly lower load than the control group which was prepared with no notch, was 4539.5 N; SD 786.4 (p = 0.001).

![Load-to-Failure for Single-leg Stance](image)

**Figure 12. Load-to-failure for single-leg stance testing**

A notch size of < 2mm in either the anterior or posterior femoral neck displayed no significant effect in weakening the construct (p ≥ 0.985) compared to the control. A 5mm notch also had no significant deviation from the control as the posterior notch group fractured at a mean value of 3988.1 N (p = 0.902) and the anterior notch group at 3374.6 N (p = 0.155). Although the 5mm anterior notch group did not show a significant difference when tested in single-leg stance, the lower load prior to fracture may be evidence that an anterior neck notch has a larger role in femoral neck strength than a posterior notch.
Load-to-failure of specimens in flexion or extension:
Both the anterior 5 mm notch group in flexion (3048.1 N; SD 509.2, p=0.027) and the posterior 5 mm notch group in extension (3104.6 N; SD 592.7, p=0.038) displayed significantly lower compressive loads than the axially tested control.

In addition, we compared the notched group in flexion to a control group fitted with a BHR and devoid of notching also tested in 25 degrees of flexion (3774.4N; SD 552.4). When controlling for the effect of positioning, the anterior notch continued to show a significant reduction in the load-to-failure value (p=0.05).

Figure 13. Load-to-failure for testing in flexion and extension
Table 4. Load-to-failure results for each experimental group

<table>
<thead>
<tr>
<th>Testing Group</th>
<th>Mean load-to-failure (SD)</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutral (Control)</td>
<td>4539.45 N (786.43)</td>
<td></td>
</tr>
<tr>
<td>Posterior 2mm</td>
<td>4208.09 N (1079.81)</td>
<td>p=0.994</td>
</tr>
<tr>
<td>Posterior 5mm</td>
<td>3988.07 N (728.59)</td>
<td>p=0.902</td>
</tr>
<tr>
<td>Anterior 2mm</td>
<td>3926.62 N (894.17)</td>
<td>p=0.843</td>
</tr>
<tr>
<td>Anterior 5mm</td>
<td>3374.64 N (345.65)</td>
<td>p=0.155</td>
</tr>
<tr>
<td>Posterior 5mm in 25° extension</td>
<td>3104.61 N (592.67)</td>
<td>p=0.038</td>
</tr>
<tr>
<td>Anterior 5mm in 25° flexion</td>
<td>3048.11 N (509.24)</td>
<td>p=0.027</td>
</tr>
<tr>
<td>Superior 5mm</td>
<td>2423.07 N (424.16)</td>
<td>p=0.001</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Testing Group</th>
<th>Mean load to failure (SD)</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control in 25° flexion</td>
<td>3774.41 N (552.4)</td>
<td></td>
</tr>
<tr>
<td>Anterior 5mm in 25° flexion</td>
<td>3048.11 N (509.24)</td>
<td>p=0.049</td>
</tr>
</tbody>
</table>

4.5 Discussion

As hip resurfacing is emerging as treatment for osteoarthritis in younger patients it is often important to these patients to be able to continue their active way of living, which can place high demands on the resurfacing component. Hip resurfacing arthroplasty is a technically difficult procedure due to multiple factors; patients tend to be more muscular which often reduces the quality of the exposure, the small head/neck ratio increases the risk of impingement, and it is important to have a valgus femoral component.\(^8,15\) In addition, as the surgeon angles and translates the femoral component to restore head-neck offset and normal anatomy there is a risk of notching the anterior or posterior femoral neck. Furthermore, during various sports and activities of daily living the femur experiences loading while flexed or extended, resulting in the anterior and posterior femoral neck experiencing similar biomechanical properties as the superior neck.\(^13,14\)

The importance of avoiding notching the superior femoral neck has been established in the literature and reinforced through the use of Finite Element Analysis (FEA). FEA has demonstrated that the stress riser created by the BHR component is due to the disparity of the relatively stiff cobalt chrome prosthesis and the relatively flexible femoral neck. In addition, a superior femoral neck notch will further concentrate stress at the rim of the femoral component, dramatically increasing the risk of femoral neck fracture.\(^12\) Our findings for superior femoral neck notching are in agreement with previous studies showing a significant decrease in strength...
and increasing the risk of fracture.\textsuperscript{7,16,17} The load applied to the notched femur prior to fracturing was approximately 46\% less than the control group.

In addition to superior neck notching significantly weakening the implant construct, our findings showed that an anterior 5mm notch can weaken the femoral neck and increases the risk of fracture particularly during activities of daily living or other activities that place a load on the femur while in flexion. With so much emphasis placed on the importance of patient selection to the outcome of hip resurfacing and as the young active male is considered to be an ideal candidate, it is important for these younger patients to be able to remain active after the surgery. An important consideration in the event of an anterior femoral neck notch is the functional range of motion. With such a decreased offset, impingement would certainly be a significant risk and would potentially warrant a revision on that basis alone.

We did not include a control group with the femur in extension because we observed that the effect was less than that with the anterior notch when tested in single-leg stance. It is also thought that loading in extension occurs far less frequently and may not have the same clinical importance as anterior notching.

For the surgeon it important to note that notching in any area of the femoral neck significantly weakens the proximal femur and consideration for a total hip is warranted. If the notched resurfacing component is left in place, one should consider modifying the rehabilitation protocol to limit the impact loading early on in the recovery.

Further research may include observing the effect of implant size on the strength of the femoral component as well as investigating various biomechanical tests using synthetic femurs with the addition of simulated muscle attachments.

\textbf{4.5.1 Limitations}

The use of composite femurs for biomechanical testing does have some limitations. Primarily, with the absence of the protective effect of muscle attachments around the hip, the study will model higher tensile stress in the neck than would be experienced in vivo. Despite the differences in magnitude of force, the mechanical principles remain the same. There have been many studies validating the use of composite femurs to replicate mechanical properties of cadaveric bones with respect to axial and torsional rigidity.\textsuperscript{10,11} The main benefit to using
composite bones over cadaveric specimens is the uniformity of each sample and the ability to avoid the difficulties that arise with the different geometries and bone densities of cadaveric bones. However, the standardized sample does limit the ability to generalize our findings.

4.6 Conclusion
This work highlights the detrimental effect of femoral neck notching during hip resurfacing. Anterior or posterior neck notching does not appear to affect proximal femoral strength in axial loading but does significantly weaken the resurfacing construct when the femur is in flexion or extension. As a result, a fracture is more likely to occur with stair climbing rather than normal walking given the reduction in strength noted after testing in flexion. As the BHR is designed for younger more active patients, these patients are more likely to test the strength of the resurfacing construct and thus these findings are important to all patients returning to the activities of daily life.

4.7 References


CHAPTER 5
MEASURING FEMORAL IMPLANT VERSION

Intra and inter-observer reliability of three different radiographic methods of measuring femoral component anteversion in hip resurfacing arthroplasty

5.1 Abstract
The purpose of this study is to assess the intra and inter-observer reliability of three radiographic methods of measuring femoral implant alignment in the lateral plane, in patients who have undergone hip resurfacing arthroplasty. Fifteen post operative lateral radiographs were analyzed by three different observers on two occasions. Each observer measured the stem-neck angles (SNAs) of the postoperative digital radiographs using the three methods. The effect of femoral position on SNA measured by digital radiographs was also investigated using a resurfaced synthetic femur. Radiographs were taken with the synthetic specimen positioned in 10 degree increments of rotation and flexion. The Isthmus technique proved to be more reliable than the other two techniques, and each of the three methods was equally accurate. Further, we found that patient malposition during radiographic imaging does not affect the measurement SNAs.

5.2 Introduction
Hip resurfacing arthroplasty has been established as a treatment option for osteoarthritis in the young, active patient and demonstrated mid-term survivorship of 95-96%.1-3 Clinical outcomes in hip resurfacing are partially dependant on accurate positioning of the femoral component.4,5 Correct placement of the femoral component helps avoid complications such as femoral neck notching and varus alignment which have been shown to increase the risk of femoral neck fracture.6-8 While much research has focused on implant position in the antero-posterior (AP) plane and the avoidance of superior neck notching, there is a paucity of investigation on measuring femoral component angulation in the lateral view. The positioning of the implant in the lateral plane is arguably as important to that of coronal implant alignment. The combination of proper component version and translation can maximize post-operative range of motion and avoid femoroacetabular impingement.9 Correct implant position in both AP and lateral plane is a
factor that affects joint tribology and kinematics.\textsuperscript{10} Despite the importance of measuring lateral placement, in practice this is commonly performed with a simple visual assessment that offers little objectivity or repeatability and may lead to the introduction of inconsistency and a high risk of human error.

A technique for the measurement of femoral component version from plain lateral radiographs has previously been described in the literature.\textsuperscript{11} This method has not been widely used and we are not aware of any validation of this technique. In an attempt to address the lack of a reliable, validated method of measuring resurfacing component anteversion from plain lateral radiographs, we have developed two further techniques that may be more accurate and reliable than the previously described method.

The purpose of this study is to assess the intra and inter-observer reliability of three methods of measuring implant alignment in the lateral plane in order to determine which evaluation is the most appropriate for use in radiological evaluation of hip resurfacing.

\textbf{5.3 Methods}

Fifteen individuals were selected at random from a cohort of 300 patients who underwent a hip resurfacing arthroplasty between June 2006 and May 2010. Fourteen patients had a pre-operative diagnosis of osteoarthritis, and one patient had osteonecrosis. Post-operative digital cross-table lateral radiographs were used for this study. The radiographs were taken in a standardised manner, with the patient placed in supine position and the contra-lateral hip and knee flexed to elevate the limb out of the image field. The hip was internally rotated 15 to 20 degrees to account for femoral neck anteversion, provided the patients range of motion allowed for it. The x-ray beam was angled 45 degrees from the long axis of the body in the cephalad direction and centered on the femoral head, perpendicular to the neck of the femur. The cross-table lateral is a standard method commonly used for taking hip lateral radiographs and was used in this study as it provides a clear view of both the anterior and posterior cortices.\textsuperscript{12} Good quality cross-table lateral radiographs allow not only good visualisation of both cortices, but show much of the femoral neck and reveal only a small amount of the lesser trochanter – thereby precluding the greater trochanter from obstructing the view of the femoral neck. Images were obtained via a computed radiography system (DirectView CR850/950; Eastman Kodak, Rochester, NY) and
were stored on our institutional PACS server (Sienet MagicStore VE50; Siemens Medical, Erlangen, Germany).

Three observers experienced in using digital radiograph templating software (MagicView 300, Siemens Medical) were asked to measure the radiographs. The observers performed the measurements using each of the following three techniques:

Resubal et al described a method of measuring femoral implant version in a study investigating computer-assisted hip resurfacing arthroplasty (the Resubal Method). Standardised frog-leg lateral radiographs were used. This method of lateral radiograph acquisition has been shown to be inconsistent over time and may also cause discomfort for the patient during imaging. The measurement method involves the observer estimating two tangential lines that best represent the anterior and posterior cortices. These two lines are then used as a basis for determining the neutral axis of the neck. The long axis of the implant stem is determined by drawing a line from the center of the stem at the base of the implant (the most proximal point) to the center of the distal tip. Implant version is the angle subtended by the long axis of the stem and the neutral axis of the neck (Figure 14).

We have modified the Resubal Method in an attempt to increase the accuracy (the Modified Resubal Method). Straight lines are used to approximate both the anterior and posterior femoral neck, and a circular templating tool is used to find the mid-point at each of the most proximal and most distal parts of the neck, which are then connected in order to determine the center of the neck. The angle between the stem axis (measured as described above) and the neutral axis of the neck is then measured (Figure 14).

In addition, we proposed the Isthmus Method for this study. The narrowest point in the neck (isthmus) is identified. A line is then drawn from the anterior cortex to the posterior cortex at the site of the isthmus. Two parallel lines are then drawn, one approximately 5 mm proximal and one 5 mm distal to the isthmus line, connecting the anterior and posterior cortices. The midpoints of these two parallel lines are then connected and represent the neutral axis of the neck. The angle between the stem axis (measured as described above) and the neutral axis of the neck is then measured (Figure 14).
The three observers performed the Resubal, Modified Resubal and Isthmus Methods on all 15 post-operative radiographs. The observers were blinded from previous measurements and the radiographs were presented in a randomised order. Each observer repeated the measurements with a minimum interval of 14 days. The order of radiographs was also randomised in order to reduce recall bias. As a measure of accuracy, the average stem-neck angle calculated from each observer’s two measurements was compared to an angle that was calculated using a computer-assisted method.

5.3.1 Description of computer measurement

The lateral radiographs were examined with an image analysis software package (Amira 5.1, Visage Imaging, Berlin). The neck and implant stem were segmented within the radiograph using a threshold-based segmentation. Manual segmentation techniques were employed to avoid inclusion of other landmarks due to superposition in the radiograph. The boundary surfaces were digitized using evenly spaced points over the length of the anterior and posterior edges of the femoral neck and the implant stem. For both the femur and the implant, the average distance between the corresponding points on the anterior and posterior surfaces was calculated, yielding two series of points; one series represented the central axis of the femoral neck and the other represented the implant stem. A linear regression was performed on each series to yield a line of
best fit, representing the neck and stem vectors. The angle between the stem and neck was calculated based on the dot product of the neck and stem vectors (Figure 15).

![Figure 15. Computer assisted measurement of SNA using Amira 5.1](image)

### 5.3.2 Rotational Analysis

In order to investigate the effect of femoral rotation on perceived stem-neck angle, we used a synthetic femur (Pacific Research Laboratories Inc., Vashon, Washington) implanted with a BHR component. The implant was positioned in neutral alignment in both the coronal and sagittal planes. The femur was then positioned to model an ideal cross-table lateral radiograph with the x-ray tube lined directly at the femoral neck to allow for a clear image of both the anterior and posterior cortices. After the ideal position was determined, images were taken at ten degree intervals of either flexion or rotation. The femur position ranged from 50 degrees of external rotation to 50 degrees internal rotation and from 50 degrees extension to 50 degrees flexion. Each radiograph was measured by two observers using the Isthmus Method. This method was chosen because it proved to be a more repeatable measure in the previous part of the investigation.

### 5.3.3 Statistics

Statistical calculations were conducted using Microsoft Excel and SPSS 16 (Microsoft Inc, Redmond, Wash and SPSS Inc, Chicago, Ill). In order to determine both the intra and inter-
observer reliability of the measurement techniques, we used an intra-class correlation coefficient (ICC). ICC’s are commonly used when conducting an assessment of consistency using continuous data; an ICC indicates the proportion of the total variance in measurement results that can be explained by differences between subjects. The ICC values range from 0 to 1, where 1 indicates perfect reliability. A high ICC indicates that measurements can be used to distinguish between individual observers; values greater than 0.75 are considered acceptable.13 A two-way random effects model measuring single-measure reliability was used, as the observers comprised a random sample from a larger population. Absolute measurement agreement was used in the statistical model because it was felt that a single measurement of stem-neck angle would likely be used clinically, rather than an average of measurements.

5.4 Results
The intra-observer repeatability ICC for the Resubal Method ranged from 0.24 to 0.78; for the Modified Resubal Method, from 0.68 to 0.79; and for the Isthmus Method, from 0.79 to 0.83.

Table 5. Mean intra-observer differences between first and second measurement of stem-neck angles

<table>
<thead>
<tr>
<th>Method</th>
<th>Observer</th>
<th>Mean Difference</th>
<th>SD</th>
<th>95% Confidence Low</th>
<th>95% Confidence High</th>
<th>Range Min</th>
<th>Range Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resubal</td>
<td>Observer 1</td>
<td>1.7°</td>
<td>1.5°</td>
<td>0.9°</td>
<td>2.5°</td>
<td>-4.7°</td>
<td>3.4°</td>
</tr>
<tr>
<td></td>
<td>Observer 2</td>
<td>2.1°</td>
<td>1.6°</td>
<td>1.3°</td>
<td>2.9°</td>
<td>-5.8°</td>
<td>4.9°</td>
</tr>
<tr>
<td></td>
<td>Observer 3</td>
<td>2.2°</td>
<td>2.0°</td>
<td>1.2°</td>
<td>3.2°</td>
<td>-1.4°</td>
<td>5.6°</td>
</tr>
<tr>
<td>Modified Resubal</td>
<td>Observer 1</td>
<td>1.4°</td>
<td>1.2°</td>
<td>-0.2°</td>
<td>3.0°</td>
<td>-3.5°</td>
<td>4.0°</td>
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<td>Observer 2</td>
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<td>1.4°</td>
<td>1.1°</td>
<td>2.5°</td>
<td>-3.1°</td>
<td>5.7°</td>
</tr>
<tr>
<td>Isthmus</td>
<td>Observer 1</td>
<td>1.6°</td>
<td>1.1°</td>
<td>1.0°</td>
<td>2.2°</td>
<td>-3.3°</td>
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<td>1.0°</td>
<td>2.9°</td>
<td>-3.9°</td>
<td>6.2°</td>
</tr>
</tbody>
</table>

The inter-observer reliability showed that the Isthmus Method was more reliable than the other techniques, displaying a noticeably higher inter-observer ICC of 0.64; however, it was slightly
less than that considered acceptable. The inter-observer ICC for the Resubal Method was 0.41 and for the Modified Resubal it was 0.37.

When comparing the measurements for each observer to the computer based measurements we used the average of the two measurements made by each observer. The mean difference from the computer based measurement for the Resubal Method was 3.1 degrees (SD, 2.9°, 95% CI, 2.3°, 4.0°, range, -10° to 12°) for the Modified Resubal Method the mean difference was 2.9 degrees (SD, 2.6°, 95% CI, 2.1°, 3.7°, range, -9° to 10°) and for the Isthmus Method, 2.7 degrees (SD, 2.35°, 95% CI, 2.1°, 3.5°, range, -7° to 9°). Statistical dispersion for each technique is shown in Figure 16.

![Difference in measured SNA's](image)

**Figure 16.** A box plot of the difference between the observers measurements and the computer based measurement.

The effect of femur position on the measurement of SNA’s can be seen in Figure 17. As the position of the femur deviates from the ideal position, represented as zero degrees on the X-axis, there is little effect on the measurement of the SNA.
Figure 17. The effect of femur position (rotation and flexion) on the measurement on stem-neck angles.

5.5 Discussion

Hip resurfacing provides a bone-preserving treatment option for young patients with end-stage osteoarthritis who wish to return to an active lifestyle. The large-diameter femoral implant allows for a range of motion similar to that of a normal hip, and there is a decreased risk of dislocation in comparison with total hip arthroplasty (THA). The benefits of hip resurfacing arthroplasty are largely dependent on the positioning of the femoral component.

If the component is misaligned in the sagittal plane, it is important for the surgeon to assess whether the anteversion will allow for enough offset between the head and the neck to avoid impinging on the acetabulum. Without the ability to accurately assess the component positioning, there is a risk that the patient will develop recurring hip pain and further damage as impingement occurs. Unlike a conventional THA, where the range of motion (ROM) is mainly limited by component-to-component contact (i.e., contact between the inner rim of the acetabular...
component and the outer surface of the femoral component neck), the ROM in HRA is mainly limited by component-to-bone contact (i.e., between the inner rim of the acetabular contact and the outer surface of the native femoral neck).\textsuperscript{9}

Similar studies have been published which assess the intra and inter-observer reliability of AP measurement techniques in hip resurfacing arthroplasty. Olsen et al. studied the measurement of femoral neck-shaft and implant angulations.\textsuperscript{16} While measuring the angles in the coronal plane are of critical importance, the positioning in the sagittal plane – another important factor – is often overlooked. With metal wear becoming an increasing issue in metal-on-metal bearing surfaces, it is increasingly important to align the resurfacing components in order to reduce the risk of increased wear.\textsuperscript{17} Hip resurfacing arthroplasty is less forgiving of malpositioned implants than THR with its metal-on-polyethylene bearings. In hip resurfacing, positioning of the implant to avoid impingement is vital since the ratio between the femoral head and femoral neck is smaller than in THR, which increases the risk of impingement.\textsuperscript{10,17}

Through assessing the reliability of these measurement techniques, we found that although the Isthmus Method was better than the others, the ICC did not quite reach the threshold for a strong correlation. According Chinn et al. however, a measurement technique should have an ICC of at least 0.6 in order to be useful.\textsuperscript{18} Difficulties in measuring the SNA may be attributable to the measurement of a very small angle, in which any variations result in a large standard deviation. In comparison to measuring the stem-shaft angle – where you compare the long axis femur to the stem of the implant – there is very little neck that can be seen clearly when measuring implant version. The impact of femoral component version with a variation of less than 10 degrees remains unclear; however, this component position may not be important clinically, and therefore measurement within a degree may not be necessary. Comparing the results of each observer to the computer calculated value, we determined that each method is similarly accurate with the Isthmus Method displaying the smallest mean difference and is capable of measuring values within a +/- 10 degree range. Angles greater than 10 degrees are considered to be significantly anteverted or retroverted.\textsuperscript{19}

5.5.1 Limitations

Templating using digital radiographs is a powerful tool for various measurements, both pre- and post-operatively. Nevertheless, there are some limitations in studying measurement techniques as
it is often difficult to standardize the images in the lateral radiographs. Often patients have significant abnormalities of the hip, which restrict the range of motion and thereby result in varying degrees of limb rotation as the radiograph is taken. It seems however, that the effect of rotation and femoral position do not greatly affect the Isthmus measurement technique.

A common area for error in the existing measurement technique of implant version occurs when the observer approximates the cortices. This is problematic as the cortices are not linear and can be obscured by the greater trochanter making it difficult to approximate with a straight line.

5.6 Conclusion

Femoral component version in hip resurfacing arthroplasty is of paramount importance to avoid mechanical failure. Measurement of anteversion on lateral radiographs is difficult given the small angles involved and difficulty in assessing the bony anatomy. We have investigated three techniques of measurement of component version on lateral two dimensional imaging. The Isthmus method has the highest intra and inter-observer reliability, and in the absence of three dimensional imaging, provides the most accurate method for measuring hip resurfacing femoral component version.

5.7 References


CHAPTER 6
IMAGELESS NAVIGATION

Imageless navigation as a learning device for hip resurfacing arthroplasty

6.1 Abstract
The clinical outcomes of hip resurfacing arthroplasty are sensitive to patient selection\textsuperscript{1,2} furthermore; they are also very susceptible to the technical details of the surgical technique.\textsuperscript{3-5} Extensive clinical research has proven that femoral neck notching, exposed cancellous and varus femoral component placement can increase the risk of femoral neck fracture, which remains the dominant mode of failure. The use of computer navigation has been shown to improve the accuracy of the femoral component placement thus reducing the likelihood of fractures.\textsuperscript{6} This study looks to assess the position of BHR components implanted using a manual jig prior to any experience with computer-assisted surgery compared to a second cohort of BHR’s implanted with a manual jig after having used imageless navigation for 187 cases. The mean deviation of the stem-shaft angle (SSA) from the target position was determined to be 5.6 degrees in the first cohort without any navigation experience and 2.2 degrees of those in the second cohort. This difference between the two groups was calculated to be statistically significant (p = 0.01). All components implanted with a manual jig after having experience using imageless navigation achieved the desired minimum of 10 degrees of valgus relative to the NSA and all were considered neutral SNA angles. This is compared to four implants which were positioned at least 10 degrees less than the target SSA position and another four which are considered retroverted. These results should encourage teaching hospitals and surgeons learning the procedure to undergo extensive training with both the conventional lateral pin jig and imageless computer navigation.

6.2 Introduction
Hip resurfacing arthroplasty is considered by many to be a conservative alternative to total hip arthroplasty in the appropriate patient demographic and has shown implant survival rates
between 95% and 96%.\textsuperscript{7-9} Hip resurfacing offers advantages over total hip arthroplasty, including conserved bone stock, enhanced stability, increased hip motion, a more normal gait, and less risk of limb length inequality making it a good treatment option for the young active patient with end-stage osteoarthritis.\textsuperscript{10} Many studies have demonstrated that the clinical outcomes of hip resurfacing are sensitive to patient selection,\textsuperscript{1,2} and also to the technique of the surgery.\textsuperscript{3-5} It has been well established that femoral neck notching, exposed cancellous bone and varus femoral component placement can increase the risk of femoral neck fracture, which remains the dominant mode of failure, representing 40% of failures.\textsuperscript{11} Hip resurfacing is described as a more difficult technique than a standard THA because retaining femoral head does not allow easy visibility of the acetabulum, and the procedure is less forgiving of misaligned component placement.\textsuperscript{10} Della Valle et al. reported on 537 cases of hip resurfacing when the BHR was introduced in the United States. The overall revision rate was high (3.1%) including 10 femoral neck fractures within the first year and three instances of notching that have not resulted in neck fracture. All fractures occurred in the first 25 cases performed, and of the three cases of notching, two occurred within the first 10 patients in the surgeons’ series and the third occurred at case 25. Two were treated with protected weight bearing for 6 weeks and have been seen at one year without any associated sequelae. The third femoral neck notch was converted intra-operatively to a THA.\textsuperscript{12}

The use of computer navigation has been shown to improve the accuracy of the femoral component placement, thus reducing the likelihood of iatrogenic mechanical fracture.\textsuperscript{6} The ability to navigate the femoral component during hip resurfacing is of great value, especially in a procedure with a steep learning curve. Studies have shown that computer-assisted surgery led to a reduction in the length of the learning curve for beginners in hip resurfacing and improved the surgeon’s ability to perform this procedure safely.\textsuperscript{13} Despite these demonstrated advantages imageless navigation is sparsely used in many surgical centres. This may be because of high costs associated with purchasing the equipment. Nonetheless, there could still be a role for computer assisted navigation at teaching centres, for use as a learning tool in collaboration with manual jigs. This study compares the position of a cohort of BHR components implanted using a manual jig without prior computer-assisted surgical experience to a second cohort of BHR patients implanted with a manual jig after having used imageless navigation for 187 cases. By improving the surgical training of those learning a new procedure, it may decrease the learning
curve for using the manual jig and consequently curtail surgical complications during the surgeons’ early cases.

6.3 Methods

Two cohorts were selected from a larger series of patients who underwent a Birmingham Hip Resurfacing from December 2004 to February 2011 on the basis that the surgery was performed without the assistance of imageless navigation to place the femoral component. All resurfacing included were performed by a single surgeon (EHS) using a conventional lateral pin jig (Smith and Nephew, Tennessee, USA). The introduction of the imageless navigation unit (VectorVision SR, BrainLAB, Feldkirchen, Germany) occurred in October of 2005.

The first cohort included 17 individuals who had their surgery between December 2004 and October 2005. Of these, 16 patients had a pre-operative diagnosis of osteoarthritis and one patient was diagnosed with avascular necrosis (AVN). The group included 15 males and two female patients, and there was an average BMI of 30.5 for the entire cohort. The second cohort included 9 individuals who had their surgery between December 2008 and February 2011. The group included 9 males all with the pre-operative diagnosis of osteoarthritis and an average BMI of 28.7.

An observer experienced in using digital radiograph templating software (MagicView 300, Siemens Medical) was asked to measure the radiographs, and was blinded to all patient data and operative dates in doing so. The observer measured the component position in both the coronal and sagittal planes. The coronal position included the measurement of the stem-shaft angle (SSA). This is the angle created by a line drawn to represent the diaphyseal axis of the femur, with another line drawn from the center of the prosthesis along the angle of the component stem toward the lateral cortex of the femur, intersecting the femoral shaft axis. The second angle measured is the femoral component version in the sagittal plane, the stem-neck angle (SNA). Similarly the SNA was defined as the angle subtended by the neck and component stem axis. In addition to the angles of the component, the observer noted the presence or absence of femoral neck notching. Post-operative digital AP and Cross-table x-rays were used for this study. Images were obtained via a computed radiography system (DirectView CR850/950; Eastman Kodak, Rochester, NY) and were stored on our institutional PACS server (Sienet MagicStore VE50; Siemens Medical, Erlangen, Germany).
The observer’s measured values for the component position were compared to the pre-operative planned position determined by the lead surgeons’ (EHS) surgical protocol. The pre-operative plan was to position the component in 10 degrees of valgus relative to the native neck-shaft angle (NSA) and to have the stem neutral in the sagittal plane. The component is considered neutral if the anteversion or retroversion value is less than 10 degrees.\textsuperscript{14} This position is considered to optimize the biomechanics of the implant construct and improve the strength of a varus femoral neck while keeping the risk of notching and exposed cancellous bone to a minimum.\textsuperscript{15} Statistical calculations were conducted using Microsoft Excel and SPSS 16 (Microsoft Inc, Redmond, Wash and SPSS Inc, Chicago, Ill). Descriptive statistics were used to calculate the differences between the final component placement and the target position. A two sample t-test was then used to compare the values from the two cohorts.

### 6.4 Results

The mean deviation of the SSA from the target position was determined to be 5.6 degrees (SD, 4.3°, 95\% CI, 3.6°, 7.6°) in the first cohort – the one performed without prior navigation experience – and 2.2 degrees (SD, 2.2°, 95\% CI, 0.8°, 3.7°) of those in the second cohort. This difference between the two groups was calculated to be statistically significant (p = 0.01). In addition, the implant placement in the first cohort erred in the varus direction which could increase the risk of femoral neck fracture. Furthermore, the variance of cohort one was determined to be 17.6 degrees compared to only 4.9 degrees in cohort two; this shows that the number of outlying implant positions is greatly reduced.

With respect to component version, the mean deviation from the target SNA of cohort one was 7.3 degrees (SD, 5.3°, 95\% CI, 4.8°, 9.9°). The second cohort had a mean difference of 4.0 degrees (SD, 2.2°, 95\% CI, 2.6°, 5.4°); this value is also significantly less than cohort one (p =0.03). The range for the implant positions in cohort one was -17.2° to 5.8° as compared to -8.2° to 3.6° for cohort two. This demonstrated that the positioning for cohort two was less extreme. Further, four of the 17 implants in cohort one were considered to be retroverted (>10°).
Figure 18 - A comparison of the accuracy of the implant positioning using a manual jig between the pre-navigation cohort and post-navigation cohort.

Figure 19 - A box and whisker plot of the coronal plane accuracy of the two cohorts.
6.5 Discussion

Hip resurfacing provides a bone conserving option for the young, active patient demographic with adequate bone stock. For males with an implant size of 50mm or larger it has shown better outcomes than the total hip replacement at nine years follow up. In addition to patient selection, surgical technique contributes greatly to the clinical outcomes of the procedure. In spite of many advances in surgical technique, femoral neck fracture remains a concern with hip resurfacing and continues to be the most common reason for revision. The etiology of femoral neck fractures in hip resurfacing has been studied at great length. Although the causes are often multi-factorial, the biomechanics of implant alignment play a large role in construct strength. Previous biomechanical studies investigating implant alignment have shown that relative valgus alignment of the femoral component strengthens the proximal part of the femur and may be protective against neck fracture. By optimizing the femoral stem-shaft angle toward a valgus
orientation during the preparation of the femoral head, this allows a resurfaced hip to transmit the load through a narrow critical zone in the femoral head-neck region; the valgus angulation may reduce these stresses on weaker areas of the anatomy. Results from such biomechanical testing suggest that a minimum of 10° of relative valgus alignment increases the proximal femoral strength of the resurfaced femur with varus native neck geometry. In femurs with more valgus native geometry, the benefit of increased proximal femoral strength is not achieved until an alignment of 20 degrees of relative valgus is obtained. The mean NSA for cohort one and two were 132 and 130 degrees respectively. The results also indicate that the proximal femoral strength of the intact femur is achieved in a resurfaced femur with an absolute implant alignment of 142°. Positioning the component in 20° of relative valgus does increase the risks of femoral neck notching, exposed cancellous bone, lack of superior medial support and internal femoral notching as discussed earlier; therefore, there may be little benefit in such a large amount of relative valgus orientation once absolute valgus alignment of 142° is exceeded. In a biomechanical study by Nabavi et al observing the load-to-failure values using synthetic femurs, they determined that, compared to the intact femurs, notching weakened the construct by 46% with the implant in valgus and 57% with the implant aligned with the normal anatomy.

Despite this knowledge, implants may end up in a varus position or with notching on the femoral neck. This may be attributed to the difficulty of the procedure or the lack of experience of the surgeon. It has been well documented that computer assisted surgery by way of imageless navigation functions to curtail implant misalignment. In particular, this is well shown in a study that retrospectively compared 51 consecutive hip resurfacings performed using imageless computer navigation with 88 consecutive hip resurfacings performed without navigation. All patient demographics were similar and there were no differences in average NSA. When the postoperative stem-shaft angle was compared with the planned stem-shaft angle, there were 33 patients (38%) in the non-navigated group with a deviation greater than 5 degrees in contrast to none in the navigated group. In addition, there was notching present in four of the patients in the non-navigated group and none in the navigated group. One major criticism of using imageless navigation is the addition of operative time. However, in this study, the average operative time was 111 minutes for the navigated group and 105 minutes for the non-navigated group. An increase of 6 minutes did not excessively lengthen the procedure, and it decreased the number of patients with potentially undesirable implant placements.
As an imageless navigation unit costs approximately $200 000, it is likely not a feasible option for all surgical centres, particularly those that perform only a small number of hip resurfacings per year. The results showing improved accuracy using the manual jig after training with computer navigation may encourage teaching hospitals to incorporate the computer assisted surgery into their treatment protocol. All components implanted with a manual jig after having experience using imageless navigation achieved the desired minimum of 10 degrees of valgus relative to the NSA and all were considered to have neutral SNA angles. This is compared to four implants which were positioned 10 degrees less than the target position and another four which were considered retroverted. There have been no reported failures or revisions of any of the components at an average of 4.7 years follow-up (0 to 7 years). The improved use of the manual jig may be attributable to an increased familiarity with the location of the optimal insertion point. Often the native anatomy of the end-stage osteoarthritis patient is greatly deformed with osteophytes and remodelled bone which can distort the surgeon’s perception. This is primarily problematic when using a manual jig, as it will often depend on a visual assessment of the guidewire.

6.6 Conclusion

Although computer assisted navigation has been shown to provide an accurate and repeatable means of implanting the femoral component, this study demonstrated that accurate positioning and successful clinical outcomes can also be achieved by using a manual jig. These results should encourage teaching hospitals and surgeons learning the procedure to undergo extensive training with both the conventional lateral pin jig and imageless computer navigation. As the success of hip resurfacing is sensitive to both surgeon technique and patient selection, the procedure may only be a viable alternative to THA if it can be adequately taught to surgeons and diligent patient selection is employed.
6.7 References


CHAPTER 7

General Discussion

From patient selection to patient recovery there are many factors of the hip resurfacing procedure that contribute to its outcome. An extensive review of existing work was conducted to establish a firm understanding of the current concepts. Accordingly, the research performed throughout this thesis attempted to answer questions that fill gaps that were apparent in the existing literature, with a view to furthering research and knowledge in the field of hip resurfacing arthroplasty.

Pre-operative templating is the first phase in preparing to position the femoral prosthesis. The goal of pre-operative templating in total hip arthroplasty includes planning for factors such as restoration of leg length and femoral offset. With hip resurfacing, however, there is limited ability to alter these variables – yet the role of pre-operative templating in hip resurfacing has been shown to play a key role in the positioning of the femoral component when using both imageless navigation and manual jigs.88 Like any hip replacement procedure, the positioning of the femoral and acetabular components is critical to the long-term success of a hip resurfacing.49,112,125 Furthermore, the acetabular and femoral components can only match each other within select ranges. Due to the limitations that the retained femoral head presents, the acetabular component is implanted first. It is therefore important to know the femoral component sizes that can be matched to a particular acetabular component, as each component can be matched with only two femoral sizes. If the femur cannot accommodate these sizes, then the acetabular component size must be altered or the plan for hip resurfacing must be abandoned in favour of a total hip replacement construct.

A recent study reviewed the results of the first 537 hip resurfacing procedures performed in the United States by 89 surgeons and concluded that these surgeons, with previously limited experience in hip resurfacing, had a revision rate of 7.4% at one year.123 These high early revision rates during the first 12 months are believed to be related to the more challenging surgical technique and the need for high-level accuracy of component positioning.124 The likelihood of femoral neck fracture is increased with risk factors linked to surgical technique,
including notching of the superior part of the femoral neck, varus femoral placement relative to the anatomical neck and exposed reamed cancellous bone.126-128

In addition to the risk of misalignment in the coronal plane during the learning period, the risk for misalignment in the sagittal plane is significant.

![Cross-table lateral x-ray of right femur with BHR in neutral alignment (left) and with BHR in extreme retroversion (right)](image)

**Figure 21.** Cross-table lateral x-ray of right femur with BHR in neutral alignment (left) and with BHR in extreme retroversion (right)

In a study by Nunley et al. that examined the lateral radiographs of 650 patients, they found that the tip of the femoral stem touched the femoral neck cortex in 80 patients (12.3%), with the majority of cases having the tip of the stem touch the anterior cortex (76 of 80 or 95%). The learning curve to avoid having the tip of the femoral component touch the femoral neck cortex on lateral radiographs was significantly different (p=0.0001) between the surgeons’ first 75 cases and their second 75 cases (21% versus 4% respectively).129 This study shows that the risk for extreme misalignment exists, particularly during a learning period. In the event malalignment occurs and the tip of femoral component stem is in contact with the anterior cortex, it results in a significant reduction in the implant offset from the posterior neck. This can also result in a posterior femoral neck notch. Through our biomechanical study of anterior and posterior notching it was determined that posterior neck notching had limited effect on the loading of the femur during single leg stance compared to notching on the superior neck. Posterior notching may not affect the strength of the construct as much as other areas because less axial force is
transferred through this area of the neck in part due to the natural femoral neck anteversion. Although the study did not test a control group of resurfaced femurs in extension and devoid of notching, it found that when a resurfaced femur with an anterior femoral neck notch was loaded in 25 degrees of flexion there was a significant reduction in strength. This reduction in strength is likely attributable to the direction of the force being transferred through the notched area when in flexion. Although a notch on the posterior femoral neck loaded in extension results in lower load-to-failure than when tested in single-leg stance, there are limited in vivo loading conditions that exist. This ultimately presents less risk of mechanical fracture to the patient than an anterior notch. However, posterior notching may disrupt the extraosseous blood supply to the femoral head, which could lead to further complications.

In addition to the biomechanical effect on the load-to-failure values caused by notching, it also eliminates the horizontal offset important in range of motion. This range of motion is important because compared with conventional total hip arthroplasty, hip resurfacing arthroplasty is associated with less risk of dislocation because the hip resurfacing prosthesis has a large diameter femoral head that is similar to the anatomic femoral head in size. Although retained femoral head bone benefits range of motion and risk of dislocation, the risk of femoroacetabular impingement is increased. Beaule et. al. found that 57% of patients with advanced end-stage OA treated by hip resurfacing arthroplasty had an decreased pre-operative head-neck ratio indicative of cam-type FAI. Painful hip impingement may develop or persist after hip resurfacing if the femoral neck abuts against the metallic acetabular component or the anterior acetabular bony wall. Preservation of the low head-neck ratio after the hip resurfacing procedure may be as a result of improper implant position or the because the head and neck deformation was not addressed and corrected appropriately during surgery. With hip resurfacing, the lack of modularity on the femoral side requires the use of other means to optimise the femoral head-neck offset. This is often achieved by translating and or angling the component to restore an appropriate amount of offset. The femoral head of patients with advanced OA are often severely retroverted and extend posteriorly, and is therefore necessary to identify the neck axis in the sagittal plane or else there will be a tendency to place the femoral component more posteriorly on the neck. This posterior placement will add to the deficient anterior offset already present, which, if left uncorrected, can result in persistent pain secondary to impingement. Optimum positioning of the femoral component and correction of any underlying abnormality to maximise
the femoral head-neck offset ratio will minimise the risk of impingement and maximise the functional range of movement.\textsuperscript{132,133} In Beaule’s study of femoral head-neck offset an alpha angle of $\geq 50.5^\circ$ was determined as indicative of impingement. In 45 of 56 hips with an alpha angle $\geq 50.5^\circ$, the mean offset ratio was significantly smaller (0.13) than those with an alpha angle $< 50.5^\circ$ (0.18) ($p = 0.03$). In the same study, the average preoperative offset ratio for hip resurfacing patients was 0.14 and the restored postoperative offset was an average of 0.19. From this study it is concluded that an offset ratio $\leq 0.15$ representing a significant risk for femoroacetabular impingement.\textsuperscript{46}

Most new surgeons have relatively little experience with hip resurfacing and may have higher rates of complications early in their learning curve. Surgeons are able to use imageless navigation in order to curtail some of the risks involved during the learning process. Pre-operative templating and imageless navigation have both been shown to facilitate the accurate and precise coronal placement of the guidewire, but reliance on the data obtained by each individually may result in erroneous positioning of the implant.\textsuperscript{134} The high cost of an imageless navigation unit can limit its accessibility for various surgical centers, particularly those performing a small number of hip resurfacings a year. Our clinical series of more than 350 navigated hip resurfacings demonstrates the efficacy and utility of imageless navigation in placement of the initial guidewire and avoiding femoral head malpreparation. There were no cases of femoral neck notching or varus implant alignment in the series. On average, the postoperative stem-shaft angle differed from the planned stem-shaft angle by less than a degree. Additional surgical time has been a major criticism of computer assisted surgery. During the first 50 cases the navigation took an average of 22.1 minutes and in the last 50 cases only 13.8 minutes. With experience the navigation portion of the procedure can be completed in less than ten minutes and maintain the utmost accuracy.

In the study investigating the use of imageless navigation as a learning device, we were able to show that although navigation may be more precise and repeatable; the manual lateral pin jig can position the implant accurately. However, this accurate placement was achieved after extensive training and experience using imageless navigation. All components implanted with a manual jig after having experience using imageless navigation achieved the desired minimum of 10 degrees of valgus relative to the NSA and all were considered neutral SNA angles. This is compared to four components which were positioned 10 degrees varus to the target position and another four
which are considered retroverted prior to gaining experience with navigation. Despite the component misalignment there have been no reported failures or revisions of any of the components at an average of 4.7 years follow-up (0 to 7 years). The improved accuracy of the lateral pin jig may be attributable to an increased familiarity to where the insertion point should be. Often the native anatomy of the end-stage osteoarthritis patient is greatly deformed with osteophytes and remodeled bone which can distort the surgeons’ perception. This is an issue when using a manual jig as it relies on a visual assessment of guidewire. In addition to the increased familiarity the improved positioning may have been affected by the difference in BMI between the two cohorts. Patients with a high BMI present a challenge when performing a BHR because of the need for a clear surgical exposure. Active patients with more than average muscular build young and stiff hips add much more difficulty to the resurfacing operation. Obese patients also add a degree of difficulty with the surgical exposure but are not as much of a problem as muscular men. The learning curve for hip resurfacing has been an obstacle for many and it is clear that there is a need for more thorough training with regards to this difficult procedure. There are limitations on surgical training outside academic programs and education for hip resurfacing was primarily administered through industry sponsored courses. These instructional courses are often limited in duration and provide a varying degree of supervised surgery on actual patients. With encouraging results using the lateral pin jig after comprehensive training using imageless navigation, many teaching hospitals may consider the benefit of using the computer assisted technique in their pedagogy.

There has been much research conducted on the topic of femoral neck notching and its outcomes for hip resurfacing arthroplasty.\textsuperscript{54,65,122,126,128} Many of these studies examined the outcome of notching through prospective cohort studies which can identify the prevalence of notching related neck fracture. In many cases, however, the fractures can be multi-factorial making it difficult to judge the extent that the notching affected the strength of the femur. In the previous biomechanical studies that investigated the effect of notching, the scope was often limited to a notch of the superior femoral neck cortex and with the limb in a simulated single leg stance under an axial load.\textsuperscript{107,121} The work of Davis et al demonstrated through biomechanical testing that superior neck notches of 2mm and 5mm weakened the proximal femur by 24 and 47 percent respectively, when compared with the bone model prepared with no notch in the superior cortex of the neck. In a similar study, a notch depth of 4mm resulted in a reduction in the load-to-failure
Davis also used finite element analysis and biomechanical testing to explore the effects of the hip resurfacing component both with and without femoral neck notching on a synthetic femur. Using 2D and 3D models, their studies have demonstrated that there appears to be a stress concentration at the rim of the femoral prosthesis potentially leading to an increased fracture risk in this area even if notching is avoided. The increased stress seems to occur due to the disparity of the relatively stiff cobalt chrome prosthesis and the relatively flexible femoral neck. There is also a relative stress shielding of the cancellous bone under the femoral component, which will also further concentrate stress at the rim of the femoral component. The FEA results of this study demonstrate that the addition of a superior femoral neck notch in this area can dramatically increase both the stress and strain within the surrounding bone, leading to a potentially increased risk of femoral neck fracture. Although the FEA analysis was conducted on synthetic femurs with a notched superior femoral neck, the same principles with regard to their findings on notching can theoretically be applied to a notch anywhere on the femoral neck. The experimental design however, did not account for different loading conditions representative of activities of daily living. The magnitudes of the out-of-plane loads during daily activities can be substantial, with the anterior-posterior component of the hip reaction force reaching 7.7 times body weight during stair-climbing. The femoral neck notching research conducted during this thesis was able to investigate this gap in the literature. The out-of-plane forces experienced during activities of daily living are particularly important for resurfacing patients, as many of the ideal candidates are young active males. For these patients, the ability to return to a satisfactory level of physical activity is very important and will test the strength of the proximal femur.

Although the reported frequency of revision with the modern resurfacing designs has been relatively low, various studies have indicated that there is a risk of femoral neck fracture associated with this technically challenging procedure, and the prevalence of femoral neck fracture after hip resurfacing has been reported to vary from 0% to 9.2%. More recently, the major concern for hip resurfacing patients is the high concentration of metal ions in the blood as a result of the metal-on-metal bearing wear. The elevated blood serum ion levels of cobalt and chromium can be as high as 10 times the normal concentration and remain asymptomatic yet there is a strong association between high metal ion levels and the
development of pseudotumours. Risk factors for high metal ion concentration have been identified in various studies to include the size of the components, female gender and steep acetabular cup abduction angle. A steep abduction angle is considered to be greater than 55 degrees and can cause edge loading. This loading pattern contributes to increased localized wear around the superior lateral surface and rim of the cup as the effective contact area is reduced, thereby increasing the stresses and disrupting the fluid layer between the bearings. Current evidence indicates that the determination of satisfactory femoral-acetabular mating includes consideration of the native femoral valgus and the corresponding acetabular component lateral opening and the native femoral version and the corresponding acetabular component version. To achieve adequate bearing contact area, a femur with increased valgus needs a correspondingly lower acetabular component lateral opening angle. Similarly, a femur with increased anteversion needs a correspondingly lower acetabular component anteversion. The majority of metal ion research focuses on the acetabular abduction and anteversion angles. In addition to the positioning of the acetabular component the alignment of the femoral head prosthesis can also contribute to increased wear patterns. The ability to accurately measure femoral component placement allows for the researchers to understand how component position contributes to wear and ion levels. Having determined a means to measure femoral implant version we were then able to complete the study examining the accuracy of manual jig placement prior to, and after experience with imageless navigation.

Hart et al. conducted a prospective CT-based study examining retrieved metal-on-metal resurfacing components to determine the relationship between the angle of version and component wear for both the acetabular and femoral components. This study concluded that the acetabular abduction angle has a strong positive correlation with the rate of wear, thus reinforcing the importance of avoiding potential edge loading. Furthermore, the combined version of the acetabular and femoral components were weakly positively correlated with the rate of wear. Femoral component version was determined in this study by using the stem of the component and the posterior condylar plane, which is only possible by CT scan. Although this may be an effective way to measure femoral component version, a CT scan is not always feasible and may be an unnecessary exposure to radiation.

Patient selection is an important consideration when studying hip resurfacing arthroplasty as proper patient selection may help avoid complications and improve patient outcomes. At the time
of clinical evaluation, patient age, gender, diagnosis, BMI, bone density, quality, and morphology, activity level, leg lengths, renal function and metal hypersensitivity are all important factors when considering a patient for hip resurfacing. Some conditions can be considered to be absolute exclusion criteria such as poor bone quality, less than 35% of the femoral head remaining as a result of AVN or poor bone density – as seen in osteoporotic patients. Also, severe renal insufficiency and known metal hypersensitivity are considered contraindications and therefore require an alternate treatment option. Factors such as age, gender, component size and BMI remain a point of debate by some surgeons.

It is well established that hip resurfacing has demonstrated the best survivorship results in a young male demographic of patients (>55 to 64 years) with revision rates in patients younger than 55 years (3.2%) and those aged 55 to 64 years (3.1%). It is noted, however, that although age of the patient has been associated with prosthetic survival, it is believed that age acts as an indicator for the patient’s activity level and bone quality. This is also likely the reason female patients have shown higher rates of revision among patients younger than age 55 (6.1%) and (7.4%) for those aged 55 to 64 years. Studies such as that of Shimmin and Back reviewed 3497 hip resurfacings in 3429 patients and found an overall femoral neck fracture rate of 1.46%. The rate of femoral neck fracture in women was 1.91%, and in men it was 0.98%. The authors concluded that the difference in the complication rates between men and women is unlikely to have been due to sampling error and that overweight, older female patients appear to have a greater risk of fracture. While the literature review clearly suggests that female sex (especially if the woman is older, postmenopausal or has decreased bone mineral density) is a major risk factor for failure, the direct causality between age and revision arthroplasty is less clear. Multiple studies that assessed the impact of age on the outcome of patients who underwent hip resurfacing were unable to establish a relationship between age and revision arthroplasty.

The incorrect orientation of the femoral component during insertion can result in notching of the femoral neck, which is detrimental because of its reported association with neck fracture and damage to the blood supply of the femoral head. As mentioned earlier, in a study on composite femora a notch of 5 mm weakened the femur by 47% whereas that of 2mm weakened it by 24%. From this it can be extrapolated that a notch of 2mm in a patient receiving a femoral component of 38mm is relatively more serious than in a patient receiving a component of 55mm. Accordingly smaller patients are at greater risk of the consequences of femoral
notching. For our biomechanical study of anterior and posterior notching we determined the appropriate implant size by using the Smith and Nephew sizing instrument as well as by knowing the specific dimensions of the synthetic femur. Future studies may investigate the effect of using smaller or larger sizes on synthetic femurs in the absence of notching as it can be speculated that the less bone remaining post-implant, the less force it will be able to withstand. The impact of component size on surgical outcomes was highlighted by the comprehensive data collection of hip resurfacing patients in Australia. In 2010, the Australian Orthopaedic Association Registry identified an inverse relationship between the size of the femoral component and the risk of revision for hip resurfacing arthroplasty. A six-fold increase in the risk of revision of hips was noted when a femoral component smaller than 44 mm was used, as opposed to 55 mm or larger. This finding was true for both men and women and, after accounting for the size of the component, survivorship was found to be independent of gender.
CHAPTER 8

Conclusions

In summation, the research conducted throughout this thesis suggests that the optimal translation and version of the femoral component in the sagittal plane is determined as maximizing the amount of host bone contact with the prosthesis while correcting the anterior femoral head-neck offset without notching. The importance of avoiding notching, particularly notching on the anterior cortex was confirmed through biomechanical testing. The combination of the younger, more active patient demographic and notching of the anterior cortex will substantially increase the risk of early failure. Subsequently, the avoidance of notching will better recreate the femoral head-neck offset to allow for functional range of movement. In addition, accurate measurement of femoral component version by the Isthmus Method will help further research in areas including the means to achieve accurate component placement and analysis of component wear. Extreme femoral component alignment in the sagittal plane occurs during the preliminary learning of the procedure and thus a more comprehensive teaching methodology is necessary. Imageless navigation provides an accurate means to place the components but it also a way for surgeons to familiarize themselves with the procedure and subsequently improve their accuracy with a manual jig. Although hip resurfacing presents a unique set of risks, there has been much success when diligent patient selection and proper attention to component position are adhered to. It is hoped that the findings of this thesis will establish a sound guideline for surgeons practicing hip resurfacing, helping to ensure optimal preparation of the femoral head in an effort to avoid the need for revision and ultimately improve patient outcomes following hip resurfacing arthroplasty.
CHAPTER 9

Future Directions

The work conducted throughout my studies has covered many aspects of hip resurfacing with respect to implantation of the femoral component and avoidance of femoral neck fracture. However, there are several logical extensions of this work that present promising paths for future investigation.

First, to ensure an optimal bearing couple in hip resurfacing it is imperative that the acetabular cup be navigated in addition to the femoral head. Acetabular cup malalignment can lead to increased wear rates and higher metal ion levels, and their associated pathophysiological effects. Furthermore, there is also a greater likelihood of femoroacetabular impingement may lead to early revision. A current limitation of acetabular navigation is the patient positioning during the procedure. In order to access the anatomical landmarks the patient would have to rotate from the lateral to supine position, potentially compromising the sterility of the surgical field. Future research will test the use of more accessible landmarks to avoid moving the patient and the accuracy of acquiring percutaneous registration points. By positioning the cup and femoral components to optimally articulate with one another, many of the negative aspects of component malalignment may be avoided. Navigation appears to be the optimal tool to accomplish this task and further investigation is warranted in this area.

One major criticism of mechanical testing of fracture values using synthetic femurs or cadaveric bones is the lack of muscle attachments and soft tissue to counter the tensile stress experienced across the femoral neck. In order to confront this problem further research will be needed to determine a method for attaching muscle analogs and having representative muscle forces. Future biomechanical research will be expanded to include work with the acetabulum. Most biomechanical studies to date focus on the femur and the femoral component placement but current work is underway at developing an apparatus to allow for the cyclical testing of the acetabulum component. Using thermal imaging we will be able to quantify the stress and strain that the component experience at various abduction and anteversion angles. This will help further define a optimal acetabular implant placement.
Second, with a better sense of how to quantify the femoral position in the lateral radiograph further research can be completed with regards to determining the accuracy of imageless navigation and other jig in the sagittal plane. Furthermore, imageless computer navigation provides an attractive option to current conventional instrumentation for insertion of the initial femoral guidewire, however, the current costs of such navigation systems present an obstacle to their widespread use. Construction of more robust jigs for non-navigated hip resurfacings may provide an accurate and reliable means for guidewire insertion for those surgeons who do have access to computer navigation. There is a current shift towards the design of patient-specific alignment jigs that are manufactured for each patient based on a CT scan of the proximal femur. The development of these single use alignment jigs eliminate the need for sterilization, reduces the amount of instrumentation needed in the operating room and potentially reduces operative time. This potential reduction in operating time can consequently reduce anesthesia time, blood loss, and risk of infection.

Third, as follow-ups for hip resurfacings are now extending past ten years, one of the main concerns that exist with the metal-on-metal bearings is the effect of metal ions and their varying effects on patients. Although much of the research conducted so far involves the biomechanical effects of component placement, pursuit of future cellular research with regard to ion levels should be conducted to further understand the adverse effects, the causal relationships between bearings and ion concentration and potential ways to reduce them. With metal-on-metal bearing components, there can be a significant increase in Chromium, Cobalt and Aluminum in the blood. These metals can exist as divalent ions, depending on their oxidation state and are circulated in the body and deposited in all tissues with calcium channels. The main idea is that divalent metal ions (Ca2+, Fe2+, Cr2+, Co2+, Al2+) all go through calcium channels in active tissues such as the heart, brain, muscle tissue, bone and cartilage. These transition metals are toxic to cells for a multitude of reasons and in particular, they interfere with DNA transcription. A future study could investigate the physiological response to the increase in divalent metal ions using a using a mouse model to characterize if and where these ions are deposited. Subsequently, we could then describe how they get into the cell by blocking calcium channels.
References


87. Morlock MMP, Bishop ND-I, Zustin JMD, Hahn MD-I, Ruther WMD, Amling MMD. Modes of Implant Failure After Hip Resurfacing: Morphological and Wear Analysis of 267


