Optimizing Femoral Head Preparation in Hip Resurfacing Arthroplasty

by

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A thesis submitted in conformity with the requirements for the degree of Doctor of Philosophy
Institute of Biomaterials and Biomedical Engineering
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Abstract

Hip resurfacing is an alternative to total hip arthroplasty for the young and active patient likely to outlive traditional means of hip joint replacement. The acetabular cup is implanted in much the same fashion as an uncemented total hip arthroplasty, however, implantation of the femoral component is unique to hip resurfacing, presenting both distinct benefits and limitations. Hip resurfacing spares much of the proximal femur including the femoral neck and portions of the femoral head. This may be advantageous if the patient requires revision surgery; however, preservation of the femoral neck bears with it the risk of femoral neck fracture. The exact mechanism of neck fracture is not fully understood. Avoiding potential fracture risks is vital to ensuring optimal patient outcomes. The current work investigated mechanical femoral head preparatory factors that may predispose to femoral neck fracture. Intra-operative computer navigation is emerging as the gold-standard in orthopaedic care. In hip resurfacing, navigation may improve the surgeon’s ability to optimally implant the resurfacing prosthesis; however, much of this technology is still in its infancy and requires investigation into the accuracy and repeatability of this peri-operative tool. Pre-operative planning can assist the surgeon in optimally determining the size and position of the resurfacing components, specifically in reference to the patient’s unique anatomy, prior to performing the operation. This may aid in correct implant selection and provide a basis on which to conduct intra-operative navigation. However, the accuracy and repeatability of pre-operative planning for hip resurfacing has not yet been established. Thus, this body of work looked to establish a clear methodology for pre-operative planning, intra-operative computer navigation and surgical technique in order to optimize preparation of the femoral head, ultimately reducing the risk of femoral neck fracture in hip resurfacing.
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CHAPTER 1
INTRODUCTION

1.1 Early Generations of Hip Resurfacing Arthroplasty

Surgeons and patients have been searching for solutions to degenerative joint disease long before the advent of joint replacement. The first total hip replacement was performed in the late 1940’s and has been considered the gold standard in hip arthroplasty ever since. However, prior to the inception of total hip arthroplasty, the idea of replacing the articular surfaces of the degenerative joint was explored. Dr. M.N. Smith-Peterson was the first to perform a hip resurfacing arthroplasty in 1923 (1). He interposed a temporary thin hemispherical shell between the femoral head and acetabulum. The aim was to regenerate the worn and damaged articular cartilage using the temporary shells and called this technique a two-stage mould arthroplasty. The shells were originally made of glass, celluloid, pyrex, and Bakelite but the performance of these materials in situ was less than optimal often resulting in severe inflammatory reaction to the material wear debris in the joint. As a result, Smith-Peterson investigated new and emerging materials including a new alloy of cobalt, chrome and molybdenum. Dr. Smith-Peterson first introduced a metal mould arthroplasty from this material in 1938, coined the Smith-Peterson Cup.

Endeavouring to explore new materials in joint arthroplasty, and learning from the tribulations of Smith-Peterson, Dr. Robert Judet introduced an acrylic femoral resurfacing implant in 1946. This implant failed in a similar fashion to previous resurfacing implant attempts, eliciting similar osteolytic reaction within the hip joint and surrounding tissue (2). In the early 1950’s, the concept of a double cup arthroplasty was introduced in which both the femur and acetabulum were fitted with articulating prostheses. John Charnley was the first to develop a total hip resurfacing system of this nature using Teflon as the bearing material in an effort to minimize friction and limit surface wear. Severe osteolysis and Teflon wear debris lead to catastrophic failure of the majority of the implanted prostheses and the use of Teflon as a bearing material was quickly discontinued. The first cobalt-chrome metal-on-metal articulation was introduced by Charles Townley in 1962 (3). His design was the first to incorporate a metaphyseal alignment
stem. Unfortunately, the metallurgical and manufacturing limitations of the time severely handicapped the metal-on-metal bearing from the outset. In addition, a lack of solid implant fixation at the bone-implant interface was to blame for failure of many of the first generation components and this became a major focus of future hip resurfacing designs.

What was coined as the second generation of hip resurfacing emerged in the mid-1970’s. This generation of hip resurfacing prostheses incorporated new bearing materials and refined surgical techniques that again breathed life into a bone conserving method of hip joint replacement. The concept of cementing components to obtain rigid initial fixation became prominent and looked to eliminate many of the problems previously encountered with free-fixation or cementless designs. During this time, surgeon-designers including Freeman, Wagner, Amstutz, Paltrinieri and Trentani and Eicher and Capello introduced surface replacement systems employing a bearing couple of a metal or ceramic femoral component coupled to a polyethylene acetabular cup (4-7).

The clinical results of these implants were again disappointing due in part to the disparity in bearing surface materials resulting in excessive wear debris in the joint. 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 (8-13). Consequently, hip resurfacing as a joint replacement therapy was largely abandoned in the 1980’s.

1.2 The Third Generation of Hip Resurfacing

In the early 1990’s, the concept of a metal-on-metal bearing couple was re-visited by Derek McMinn and Ronan Treacy (14). The initial McMinn prosthesis design consisted of a press-fit cobalt-chrome stemmed femoral component and a press-fit, smooth-backed acetabular cup. Further design iterations included hydroxyapatite coated bone-interfacing surfaces and cemented fixation. The final design became the Birmingham Hip Resurfacing (BHR, Figure 1). Building on earlier experiences with the THARIES, Harlan Amstutz quickly followed suit with the Conserve surface replacement system 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 (15). 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 femoral component exhibits a short metaphyseal stem used for alignment purposes during implantation, a design feature not present in earlier generations.

Figure 1. Birmingham Hip Resurfacing (BHR) system. A) The acetabular cup has a porous, beaded hydroxyapatite backing while the femoral component exhibits a short metaphyseal alignment stem; B) Left hip resurfaced with a BHR (Images courtesy of Smith & Nephew Inc., Memphis, TN, USA)

Hip resurfacing is now becoming an established alternative to total hip replacement in the young, high demand patient with end-stage hip arthritis. Many of the complications and early failures of the previous generations of hip resurfacing appear to have been eliminated with the most recent hip resurfacing systems. The literature now contains excellent short and medium term results of the new generation of hip resurfacing (16-20). 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. However, concerns over the risk of implant failure persist.

1.3 Hip Resurfacing Failure

An increased risk of implant failure has been attributed to two major failure modes in hip resurfacing. 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 insult to the femoral head during reaming preparation or stress shielding by the stiff femoral component. The second and more catastrophic failure mode is femoral neck fracture. Neck fracture typically occurs in 1-2% of patients (16;19;21-27) and within the first 3 to 4 months post-operatively (21;27;28). Failure within this short time frame has lead to the suggestion that iatrogenic mechanical error during preparation of the femoral head, including femoral neck notching, varus implant alignment and failure to fully seat the femoral component, may be the root cause of early resurfacing failure (16;19-30).

Femoral head malpreparation may be the result of a number of different surgical factors including: inappropriate implant selection due to an inaccurate or poorly executed pre-operative plan, inaccurate femoral guidewire insertion with the use of conventional guidewire alignment instrumentation, reliance on inaccurate computer generated data during navigation, and careless reaming preparation of the femoral head. There has been limited investigation into the different factors that may contribute to femoral head malpreparation in hip resurfacing supporting the premise of this thesis in investigating and exploring the multi-factorial nature of femoral neck fracture.

1.4 Thesis Objectives

The aim of the current work is to establish a comprehensive methodology for hip resurfacing that includes guidelines for pre-operative planning, intra-operative computer navigation and femoral head preparation. The objective of investigating these three key areas of the hip resurfacing
procedure is to provide a basis on which optimization of femoral head preparation can occur. It is intended that establishing a sound methodology for femoral component selection and placement will help surgeons minimize the learning curve associated with this demanding form of hip replacement, help reduce the incidence of femoral neck fracture caused by mechanical preparatory error and most importantly, help improve the longevity of the joint replacement ultimately improving patient outcomes.

1.5 Thesis Outline

The thesis examines three major topics within the hip resurfacing procedure and consequently will be broken into three major areas of investigation. The topical sequence of the chapters will in turn represent the chronological order of the operation for implantation of the femoral hip resurfacing component. The present work is comprised of a series of studies previously published in, or currently under review by, academic journals as part of the author’s doctoral dissertation.

Chapter 2 will analyze the process of pre-operative planning and implant selection. Observer reliability in estimation of anatomical axes and implant size selection will be discussed along with their implications for computer navigation and surgical preparation.

Chapter 3 will explore intra-operative computer navigation for placement of the femoral component. The subject matter therein will consider the utility of computer navigation in a clinical series, the effectiveness of navigation in patients with abnormal femoral anatomy, the accuracy and precision of imageless navigation compared to conventional instrumentation, as well as the accuracy and reliability of computer generated data for implant placement planning.

Chapter 4 will look at femoral head preparation. Three major femoral neck fracture risks have been identified in the clinical literature including femoral component alignment, femoral neck notching, and exposed cancellous bone. There exists a paucity of biomechanical investigation into femoral neck fracture precursors and this chapter explores these factors via mechanical testing of synthetic and cadaveric femora as well as computational modeling.
Finally, the thesis will conclude with a summary chapter. This section will review the major findings of the thesis highlighting the integration of the three areas of investigation into a cohesive methodology for optimal femoral head preparation in hip resurfacing. This chapter will also provide directions for future work.

1.6 References


CHAPTER 2
PRE-OPERATIVE PLANNING

2.1 Prologue

Pre-operative planning affords the surgeon an opportunity to plan much of the hip resurfacing procedure prior to performing the operation. A pre-operative plan provides a means to select appropriate implant sizes and align the implants in an optimal position specific to the individual patient’s anatomy. Pre-operative templating incorporates estimating various anatomical parameters and selecting appropriate implant sizes and as such is susceptible to measurement error and observer variability. In addition, magnification errors and patient malposition during radiography present obstacles to the accuracy of this method and may even predispose to femoral head malpreparation. This chapter explores the accuracy and reliability of pre-operative planning for clinical use in hip resurfacing. This chapter is comprised of two refereed journal articles, one published and one currently in press (Olsen et al. 2009a, Olsen et al. 2009b).

2.2 The Reliability of Radiographic Assessment of Femoral Neck-Shaft and Implant Angulation in Hip Resurfacing Arthroplasty

2.2.1 Abstract

Fifteen sets of patient radiographs were analyzed by 3 different observers on 2 occasions. Each observer measured the femoral neck-shaft angles (NSA) of the pre-operative digital radiographs and stem-shaft angles (SSA) of the post-operative radiographs. The effect of femur position on stem-shaft angle measured by digital radiographs was also investigated utilizing a resurfaced synthetic femur. Radiographs were taken with the synthetic specimen positioned in 10 degree increments of either flexion or rotation. Measurement by digital radiographs proved less than optimal in assessing pre-operative neck-shaft angle but was better in assessing the post-operative component stem-shaft angle. External rotation of 30 degrees and flexion of 40 degrees resulted
in a clinically significant disparity in SSA measurements. Patient malposition during radiographic imaging can contribute to erroneous NSA and SSA results.

2.2.2 Introduction

Hip resurfacing is becoming an established form of joint arthroplasty with satisfactory early to midterm results (1;2). The success of the procedure is largely dependent on the accuracy of placement of the femoral component (2;3). Avoidance of femoral head malpreparation including femoral neck notching and varus implant alignment is critical in avoiding early failure of the resurfaced femur (4-11). The traditional method of femoral head preparation involves pre-operative assessment and templating of the proximal femur by means of anteroposterior (AP) hip or pelvic radiographs followed by the use of a mechanical jig fixed to the proximal femur to insert the initial guidewire. A great deal of inconsistency can result between the planned implant position and the end result with use of conventional guidewire alignment instruments in hip resurfacing (12).

Methods such as computer navigation are looking to improve the accuracy of implant placement in hip resurfacing, yet, thus far navigation has not proven robust enough to circumvent manual pre-operative templating of the proximal femur with a paucity of investigation into the true accuracy of this method. Consequently, the chosen implant orientation in hip resurfacing remains largely dependent on accurate pre-operative templating, including neck-shaft angle (NSA) determination. Measurement by radiograph is not necessarily accurate in and of itself, particularly in the case of NSA measurement (13), and is susceptible to confounders such as patient malposition (14-18). The use of plain radiographs in measurement of anatomical parameters in lower extremity arthroplasty is well documented, as is the variability in measurement precision and accuracy afforded by this technique (14-16;19;20). However, there exists a lack of investigation into this phenomenon as it pertains to hip resurfacing. Therefore, the aim of the current study was to assess the reliability of digital radiographic measurement of the pre-operative native femoral neck-shaft angle and post-operative component stem-shaft angle in hip resurfacing arthroplasty.
2.2.3 Methods and Materials

Fifteen hip resurfacing patients were selected at random and pre- and post-operative digital radiographs were collected. Patient radiographs were selected from a cohort of 30 hip resurfacings of which the dominant aetiology was osteoarthritis. No other gross pathology warranted exclusion in the series. Three observers, trained in the templating of digital radiographs for hip resurfacing, performed NSA measurements on each pre-operative radiograph and stem-shaft angle (SSA) measurements on each post-operative radiograph. Measurements were taken in a blinded fashion on 2 separate occasions with a minimum interval of 1 week. For each measurement occasion, each observer performed 15 consecutive measurements on the entire group of the pre-operative radiographs and then the post-operative radiographs for a total of 30 NSA and 30 SSA measurements performed by each observer in the study. Radiographs were randomized between the NSA and SSA measurement groups and between the first and second measurement occasions.

NSA and SSA assessments were performed on digital AP unilateral hip radiographs. The standard positioning protocol used in the clinical series placed the patient in AP neutral position with no femoral rotation. The source to image distance was 100 cm centered over the proximal femur. The resulting image displayed the lateral pelvis and proximal two thirds of the femur. Images were obtained via a computed radiography system (DirectView CR850/950, Eastman Kodak, Rochester, NY) and were stored on an institutional PACS server (Sienet MagicStore VE50, Siemens Medical, Germany). Using digital radiograph templating software, (MagicView 300, Siemens Medical, Germany) a line was drawn along the long axis of the femoral diaphysis. This line represented the femoral shaft axis (18;21-23). To determine the NSA, a second line was then drawn from a point approximating the center of the femoral head through the midpoint of the isthmus of the femoral neck intersecting the femoral shaft axis. The resulting line represented the femoral neck axis (18;21-25). The angle subtended by the femoral shaft and neck axes represented the native NSA. Similarly, to determine the SSA, a line was 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 (Figure.2).
Figure 2. Radiographic Templating. A) Pre-operative NSA measurement. NSA is delineated as the angle subtended by the diaphyseal and femoral neck axes. B) Post-operative SSA measurement. SSA is delineated as the angle subtended by the diaphyseal and femoral component axes.

The effect of femur position on SSA measurement by digital radiographs was investigated using a synthetic Third Generation Composite Femur (Model 3306, Pacific Research Laboratories Inc., Vashon, WA, USA). The synthetic femur is a structural and geometrical analog to the human femur that has been validated to closely simulate the mechanical properties of bone with much less interspecimen variability than their biologic counterparts (26;27). Physical dimensions of the synthetic femur used in the study include a head diameter of 52 mm, a neck diameter of 37
mm, a mid-shaft diameter of 32 mm, a neck-shaft angle of 120 degrees, femoral neck anteversion angle (FNAA) of 8 degrees and an overall length of 485 mm. The synthetic specimen was prepared with a 46 mm Birmingham Hip Resurfacing prosthesis (Smith & Nephew Inc., Memphis, TN, USA). The component was implanted in 5 degrees of valgus alignment relative to the native NSA of the synthetic femur.

Neutral rotation (0 degrees) was defined as the position of the femur such that the posterior condyles were oriented parallel to the film cassette (18;22;28). The resurfaced femur was rotated in 10 degree increments ranging from 10 degrees of internal rotation to 80 degrees of external rotation. Internal rotation (IR) was assigned negative values while external rotation (ER) positive values. The resurfaced femur was then oriented in 10 degrees of internal rotation and flexed in 10 degree increments from 0 to 90 degrees. A true measure of NSA, and correspondingly SSA, is one taken in the plane of the femoral neck (29). Positioning of the femur in an internally rotated position removes much of the visual distortion of the proximal femur that can be attributed to foreshortening of the neck due to the natural femoral neck anteversion (18;28-31). Thus, an internally rotated position neutralizing the effect of neck anteversion was chosen to measure the true effect of flexion on the projected SSA.

At each increment of rotation and flexion, a radiograph was obtained to assess the SSA. SSA measurements were performed by a single observer using the same method as previously described. A second observer repeated the measurements. Measurement of SSA rather than NSA was chosen as SSA assessment proved a more repeatable measurement in the previous portion of the study. It was also felt that measurements in flexion and the direction of external rotation would be sufficient to characterize the impact of femur position on SSA measurement as extension and the direction of internal rotation would be symmetrical about each respective rotation axis.

For analysis of differences within and between groups, Excel and the statistical software SPSS13 (SPSS Inc., Chicago, IL, USA) were used. One-way ANOVA with Tukey post hoc analysis was performed comparing the differences in NSA and SSA measurements of the 3 observers. A p value of 0.05 was considered significant. An intraclass correlation coefficient (ICC) was computed to estimate the interobserver reliability in measurement. An ICC indicates the proportion of the total variance in measurement results that can be explained by differences
between subjects. ICC values range from 0 to 1 with 1 indicating perfect reliability. A high ICC indicates that measurements can be used to distinguish between individual observers with values greater than 0.75 considered acceptable (32). A two-way random effects model measuring single measure reliability was used with the observers considered a random sample from a larger sample of observers. Absolute rather than consistency measurement agreement was considered in the statistical model as it was felt that a single measurement of NSA or SSA would often be used clinically rather than an average of measurements.

2.2.4 Results

There was a significant difference between observers in mean measured angle difference in both the NSA (p=0.04) and SSA (p<0.01) groups. Frequency distributions for both the difference in NSA and SSA measurements are shown in Figures 3 and 4. The mean intraobserver difference in measured angle was 3.1 degrees (SD 2.4 degrees, 95% CI 2.4-3.8 degrees, Range 0-10 degrees) for the NSA group and 1.5 degrees (SD 2.3 degrees, 95% CI 0.8-2.2 degrees, Range 0-11 degrees) for the SSA group. The intraclass correlation coefficient for the NSA group was 0.44 and for the SSA group was 0.86. This result indicates moderate observer agreement in the measurement of NSA, though strong agreement for the SSA measurement.

The impact of femur position on measured SSA can be seen in Figure 5. The mean difference between SSA measurements of the two observers for each increment of femur position was 0.5 degrees (SD 0.5 degrees) in flexion and 1.2 degrees (SD 1.0 degrees) in rotation. Interobserver variability between the 2 observers was considered small enough to utilize only a single observer’s results in the analysis. As the resurfaced femur was rotated from -10 to 80 degrees, the nominal SSA of 125 degrees increased toward 180 degrees. In a similar fashion, as the resurfaced femur was flexed from 0 to 90 degrees, the measured SSA decreased from the nominal measurement of 125 degrees toward 90 degrees. External rotation of the synthetic specimen of 10 degrees resulted in a 3 degree discrepancy in measured SSA, while ER of 30 degrees resulted in a 10 degree discrepancy. There was found to be only 1 degree difference between SSA as measured in the internally rotated and neutral positions. Flexion of the synthetic femur of 20 degrees resulted in a 5 degree discrepancy in measured SSA while flexion of 40 degrees resulted in a 13 degree discrepancy (Figure 6).
Figure 3. Scatter plot of the differences between repeated measures of the 3 observers for pre-operative NSA. There was a significant difference between observers in measurement difference ($p=0.04$) with only moderate agreement between observers (ICC=0.44).

Figure 4. Scatter plot of the differences between repeated measures of the 3 observers for post-operative SSA. There was a significant difference between observers in measurement difference ($p<0.01$) with strong agreement between observers (ICC=0.86).
2.2.5 Discussion

With hip resurfacing again becoming a more popular form of joint arthroplasty, it is important to ensure optimal preparation of the femoral head to avoid preparation errors that predispose the resurfacing construct to premature failure (1-11). Currently, plain and digital radiographs are a common method of assessing femoral neck-shaft and component angulation both pre- and postoperatively. Proper assessment of the native NSA is a crucial step in the pre-operative planning procedure and plays a pivotal role in the intra-operative planning of femoral component placement in imageless computer navigation.

The results of the current study emphasize the susceptibility for misleading measurements in radiographic assessment for hip resurfacing. Measurement of the neck-shaft angle in the clinical series proved less repeatable than measurement of the stem-shaft angle. It is believed that due to
the presence of a clearly defined implant stem, observers are more likely to accurately assess the angle of the implant with respect to the femoral shaft axis. Greater interpretation exists when approximating the angle of the native femoral neck, as no clearly defined reference from which to gauge the angle of the neck is present. Malposition of the femur during radiography may compound the effect of measurement variability. Both rotation and flexion of the femur impacted the perceived SSA through clinically achievable ranges of motion and contributed to significant disparities in measurement.

Figure 6. Stem shaft angle measurement of resurfaced synthetic femur flexed 40 degrees
Measurement of proximal femoral geometry by goniometer or protractor has been widely employed on both physical specimens and radiographic images (18;22;24;33-38), until the recent advent of digital radiographic templating such as that utilized in the current study. The method of NSA measurement in the present study is taken from similar methods of neck-shaft angle measurement as described in the literature (18;21-23). Typically, in radiographic assessment of NSA, a line is drawn along the midline of the diaphysis of the femur representing the femoral shaft axis. The center of the femoral head is marked, often with the use of a concentric circle template, and a line is drawn connecting this point to the femoral shaft axis through the midpoint of the isthmus of the neck. The angle subtended by the intersection of this resulting neck axis and the femoral shaft axis is the femoral neck-shaft angle. This method may introduce measurement error if the femoral head is deformed or translated with respect to the femoral neck as in the case of Legg-Calvé-Perthes disease, slipped capital femoral epiphysis or advanced osteoarthritis (24;39). Inclusion of the center of the femoral head as a reference point may be inappropriate in assessment of the femoral neck-shaft angle in such cases, suggesting that a more robust method of NSA measurement may be required to ensure accuracy in component placement.

The assumption of symmetry of rotation of the femur measured in both the sagittal and transverse planes by plain radiographs is supported by the work of Kay et al. (18). The effect of femoral rotation on projected NSA was investigated through NSA measurement by plain radiographs using a protractor and by means of a mathematical model to estimate the neck-shaft angle measured in femurs with varying NSA and FNAA. The study utilized a preserved cadaveric specimen with a native NSA of 120 degrees and FNAA of 12 degrees, similar to the composite femur used in the current study with NSA of 120 degrees and FNAA of 8 degrees. Neutral rotation was defined as the position of the femur such that the posterior femoral condyles were oriented parallel to the radiograph cassette. They showed that a clinically significant difference of 10 degrees between measured and actual NSA occurred at an external rotation of greater than 30 degrees. This finding is comparable to the results in the current study. Kay et al. showed that the arc of NSA measurement was not symmetrical about the position of neutral rotation of the femur but rather the position of internal rotation that coincided with the native FNAA of the femur. By way of mathematical model, Kay et al. showed that an anatomically normal FNAA had little effect on measured NSA in external rotation of up to 30 degrees and that
only elevated native FNAAs had a significant impact on perceived NSA through smaller degrees of external rotation. They also showed that as the native NSA increased, the allowable arc of rotation of the femur increased before a clinically significant difference in measured NSA occurred.

Flexion of the femur had a similar impact on measured SSA as that of rotation. While external rotation of the femur tended to provide an overestimate of the true SSA, flexion tended to underestimate this figure. Accurate assessment of the SSA deteriorated above 20 degrees of flexion and a measurement difference of greater than 10 degrees occurred at 40 degrees of flexion or greater. Only a 1 degree discrepancy in SSA measurement was observed between the neutral and internally rotated positions and thus the effect of flexion as investigated in the internally rotated position is likely to have a similar result for neutrally positioned patients. Malpositioning of the patient or conditions which exhibit contracture of the hip with progressive hip flexion may have an impact on proper assessment of the pre-operative femoral geometry. In the current study, excessive flexion tended to obscure assessment of the femoral neck geometry. It was shown however in a recent study, that flexion improved visualization of the proximal femur when the femur was placed in external rotation of 15 degrees or greater (28). Imaging of hips that present with pathologies such as external rotation contractures or hypotonicity of the lower limbs may take advantage of hip flexion to improve visualization of the proximal femur whereas for the normal hip such positioning may introduce inaccuracies in radiographic assessment.

The assumption that the femoral shaft axis drawn on the standard AP hip radiograph closely approximated the true diaphyseal axis is a limitation in the current study. Femoral shaft bowing and deformity of the proximal femur can contribute to diversion of the approximated shaft axis from the true shaft axis and therefore can contribute to measurement error of the proximal femur (31;33). This effect may be exacerbated with the use of radiographs that display lesser amounts of the femoral diaphysis. As a result, caution must be exercised when templating using radiographs such as those utilizing the standard AP pelvic view. In addition, although the patient group employed in the study was limited in size, it was felt to adequately represent the larger population of hip resurfacing patients. The primary aetiology for the patient cohort from which the study sample was taken consisted entirely of osteoarthritis. While this aetiology is not all encompassing of those related to hip resurfacing, it is the dominant one for the population of
individuals receiving this form of arthroplasty. A further drawback of the study is the use of a synthetic femur analog for representation of the effect of patient malposition on perceived SSA. Although the synthetic femur is representative of the normal anatomy and may not necessarily represent the pathological anatomy attributable to osteoarthritis in the clinical series, it was felt that due to the fact the femur was resurfaced this would be an accurate representation of the resurfaced femur as observed clinically.

Gross miscalculation of the native NSA can have a detrimental effect on the placement of the resurfacing prosthesis, particularly the final coronal version of the component. Placement of the component in a relative varus alignment with respect to the native NSA of the femur has been speculated to predispose the resurfaced femur to neck fracture (2-11) and has been shown to biomechanically weaken the resurfacing construct (40). Determination of NSA by digital radiographs may not be the optimal method of assessment of the proximal femur and perhaps more robust methods, such as that of computed tomography imaging reconstructed in the plane of the femoral neck, may be required to achieve the level of accuracy required for optimal outcomes in hip resurfacing.

2.2.6 Conclusion

Measurement by digital radiographs was less than optimal in determining the native NSA of the proximal femur, while proving to be a more reliable method for assessment of the post-operative SSA. Patient malposition during radiographic imaging can contribute to erroneous NSA and SSA results. Positioning of the femur in external rotation of greater than 30 degrees or in flexion in excess of 40 degrees is to be avoided as this tends toward clinically significant errors in measurement. Patient positioning including neutral to internal rotation of the femur, to place the neck relatively parallel to the radiograph cartridge, and minimizing hip flexion is recommended to obtain accurate representation of the proximal femur. Caution must be taken when templating for resurfacing with radiographs that exhibit excessive femoral rotation and/or flexion as this may lead to inaccurate pre-operative planning and ultimately less optimal component placement. A more accurate method of neck-shaft angle determination is required to enable surgeons increased success in templating for hip resurfacing arthroplasty.
2.2.7 References


2.3 Assessment of Accuracy and Reliability in Pre-operative Templating for Hip Resurfacing Arthroplasty

2.3.1 Abstract

The current study investigated the accuracy and reliability of hip resurfacing component selection based on digital pre-operative templating. Four surgeons templated pre-operative radiographs on two occasions for acetabular and femoral components in 50 randomly selected hip resurfacing patients. Component selection reliability was variable amongst surgeons (κ=0.16-0.73) and fair between surgeons (κ=0.23-0.32). The average percent agreement for the acetabular component was 47% (range 32-64%) and for the femoral component was 54% (range 38-70%). Surgeons tended to underestimate implant size if the correct implant was not chosen (acetabular 29%, femoral 32%). Selection of an undersized femoral component may lead to femoral neck notching or varus implant alignment. This study emphasizes the need for intra-operative verification of pre-operative templating results to ensure optimal implant selection in hip resurfacing.

2.3.2 Introduction

Hip resurfacing offers a bone conserving alternative to total hip arthroplasty in the young, active patient. Placement of the acetabular component is similar to that of a conventional total hip, however, placement of the femoral component is unique to hip resurfacing and presents its own distinct challenges. Femoral neck notching and varus implant alignment have been identified as prominent mechanical risk factors that may predispose the resurfaced femur to femoral neck fracture (1-5). Pre-operative 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 these 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 (6-12). 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.
Pre-operative templating for total hip arthroplasty has been shown to be relatively accurate in determination of femoral and acetabular component sizes (13-16), however there is little to support the same assertion for hip resurfacing. Therefore, the purpose of the current investigation was to assess the accuracy and reliability of pre-operative templating for implant size in hip resurfacing arthroplasty.

2.3.3 Methods and Materials

2.3.3.1 Patients

Fifty patients were randomly selected from a group of 92 patients having received a hip resurfacing arthroplasty at the author’s institution. The patient cohort consisted of 42 males and 8 females. The dominant aetiology was osteoarthritis in 46 patients and avascular necrosis in the remaining 4 patients. The mean age at time of surgery was 48.8 years (SD 8.6, Range 25-69) and mean BMI was 29.5 (SD 5.2, Range 20.4-42.2). All hip resurfacings were performed by a senior surgeon utilizing a posterolateral approach with implantation of a Birmingham Hip Resurfacing prosthesis (BHR, Smith & Nephew Inc., Memphis, TN, USA) in all cases.

2.3.3.2 Study Design

Four fellowship trained surgeons each templated pre-operative digital radiographs for acetabular and femoral component sizes in the 50 randomly selected patients who underwent a hip resurfacing arthroplasty. The surgeons were familiar with templating for hip resurfacing but were not involved in the operative cases. Templates were performed in a blinded fashion on two separate occasions spanning a minimum of three weeks for a total of 100 templates performed by each observer in the study. For consistency in templating methodology, surgeons were instructed to plan the acetabular component in approximately 40 degrees of abduction and the femoral component in slight valgus orientation relative to the native femoral neck. Templates were performed on digital AP unilateral hip radiographs utilizing digital radiograph templating software (EndoMap v2.01, Hectec GmbH, Niederviehbach, Germany) (Figure 7). To minimize recall bias, radiographs were randomized between the first and second templating occasions.
A standardized positioning protocol was utilized in obtaining patient radiographs. Patients were positioned in AP neutral with no femoral rotation. A uniform scaling factor was used to scale digital radiographs prior to templating. Each radiograph was scaled to 85% of its original size and digital hip resurfacing templates were used to select the appropriate component sizes. Each standard femoral component size corresponds to one of two acetabular component sizes. Depending on the quality of acetabular bone stock and the size of the acetabulum, acetabular components can be sized 6 mm (standard) or 8 mm larger than the femoral component diameter.
2.3.3.3 Statistical Analysis

For analysis of differences within and between surgeons, Excel and the statistical software package SPSS13 (SPSS Inc., Chicago, IL, USA) were used. Templating accuracy was calculated as percent agreement between the templated and implanted components. To assess within-surgeon reliability, a Cohen’s kappa statistic was calculated to determine the level of intraobserver agreement for implant selection. For analysis of non-symmetric tables, an SPSS macro was used (17). Between-surgeon reliability in implant selection for each of the two templating occasions was expressed as a generalized multi-rater kappa statistic. An additional SPSS macro was used to compute the level of agreement for categorical data between multiple observers (18). The interpretation guideline established by Landis and Koch was used in evaluating the strength of intra- and interobserver agreement using the kappa statistic (19). This guideline rates the strength of agreement for kappa values ranging between 0.00-0.20 as ‘slight’, 0.21-0.40 as ‘fair’, 0.41-0.60 as ‘moderate’, 0.61-0.80 as ‘substantial’ and 0.81-1.00 as ‘almost perfect’.

2.3.4 Results

In approximately half of the templated radiographs, surgeons chose the correct acetabular and femoral component sizes. The cumulative percent agreement for the acetabular component was 47% (range 32-64%) and for the femoral component was 54% (range 38-70%) (Table 1). The discrepancy between the two percent agreement values is due to the two acetabular component sizes available for each femoral component size. If the two acetabular component sizes are included in the accuracy calculation, the percent agreement for acetabular component selection is also 54%. In nearly one third of the templates performed, surgeons underestimated the correct implant size by one standard component increment (acetabular 29%, femoral 32%) and by two component increments in two percent of the templates performed (Figure 8).

Interobserver agreement for the acetabular and femoral components was fair and similar between the two templating occasions (acetabular $\kappa=0.25$, $\kappa=0.26$; femoral $\kappa=0.32$, $\kappa=0.30$). Intraobserver agreement for the acetabular and femoral components was variable amongst surgeons ranging from slight to moderate for the acetabular component ($\kappa=0.16-0.56$) and slight to substantial for the femoral component ($\kappa=0.18-0.73$) (Table 1). Agreement in acetabular
templating was slight for two surgeons and moderate for two surgeons. Agreement in femoral component templating was slight for one surgeon, fair for one surgeon and substantial for the remaining two surgeons.

Table 1. Component Templating Agreement and Repeatability

<table>
<thead>
<tr>
<th>Surgeon 1</th>
<th>Correct Acetabular Component</th>
<th>Intraobserver Kappa</th>
<th>Correct Femoral Component</th>
<th>Intraobserver Kappa</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Trial 1</td>
<td>Trial 2</td>
<td>Acetabular Component</td>
<td>Trial 1</td>
</tr>
<tr>
<td>Surgeon 1</td>
<td>16/50 (32%)</td>
<td>32/50 (64%)</td>
<td>0.16 (0.08)</td>
<td>19/50 (36%)</td>
</tr>
<tr>
<td>Surgeon 2</td>
<td>16/50 (32%)</td>
<td>18/50 (36%)</td>
<td>0.68 (0.07)</td>
<td>19/50 (36%)</td>
</tr>
<tr>
<td>Surgeon 3</td>
<td>25/50 (50%)</td>
<td>23/50 (44%)</td>
<td>0.20 (0.08)</td>
<td>31/50 (62%)</td>
</tr>
<tr>
<td>Surgeon 4</td>
<td>30/50 (60%)</td>
<td>27/50 (39%)</td>
<td>0.53 (0.06)</td>
<td>34/50 (64%)</td>
</tr>
</tbody>
</table>

Average % Agreement: 43.5% Acetabular Component, 50.5% Femoral Component

Interobserver Kappa: 0.25 (0.04) Acetabular Component, 0.26 (0.04) Femoral Component

Kappa values shown with Standard Error.

Figure 8. Frequency distribution of the differences between templated and implanted component sizes. Positive values indicate larger component selection; negative values, smaller component selection.
2.3.5 Discussion

Pre-operative templating is a common tool surgeons utilize to plan both component selection and placement, however, the efficacy and utility of this tool in planning for hip resurfacing arthroplasty is unclear. The current study showed that pre-operative templating was accurate in selecting the correct acetabular component in 47% of templates and the correct femoral component in 54% of templates performed. In comparison to digital templating for total hip arthroplasty, acetabular component selection accuracy exceeded reported values ranging from 16-36% (20;21). Femoral component accuracy was similar to, or exceeded, reported values ranging from 34-58% (20;21). While these accuracy values accord with the literature, The et al. showed that digital templating accuracy for total hip arthroplasty can be as accurate as 81% for the acetabular component and 76% for the femoral component, however this included a margin of error of one component size (22).

The current work demonstrated that larger femoral and acetabular components were selected in 12% of templates performed. This finding is of some concern considering the recent work that has demonstrated that acetabular component sizes may be larger in hip resurfacing than in conventional total hip arthroplasty, drawing into question whether hip resurfacing is conservative with respect to acetabular bone stock (23). The topic of acetabular bone resection in hip resurfacing remains controversial however, as others have demonstrated that acetabular components in hip resurfacing are no larger than in equivalent total hip arthroplasty (24;25). Of greater concern was the finding that there was a tendency for surgeons to underestimate the femoral component size if the correct implant size was not chosen. While this may be of benefit for sparing of acetabular bone stock, the likelihood of femoral neck notching is greatly enhanced with the use of a smaller femoral component. The ability to place the component in a valgus orientation, or avoid varus implant alignment, is also limited with the use of a smaller femoral component. Femoral neck notching and varus implant alignment have been identified both in clinical and biomechanical studies to significantly weaken the femoral neck and increase the risk of neck fracture (1-5;26-32). In addition, the use of a smaller femoral component may reduce the joint range of motion before impingement by decreasing the head/neck offset (33;34).

Within-surgeon agreement was variable for both acetabular and femoral component selection reaching substantial for femoral component selection but no greater than moderate for acetabular
component size. Across surgeons, reliability was fair with slightly less reliability in acetabular component selection. The reduction in reliability may be the result of the greater flexibility in acetabular compared to femoral component sizing as there are two acetabular components available for each standard femoral component size.

With the advent of digital radiography and its increasing use clinically, a number of recent studies have looked at the accuracy of digital templating relative to traditional analogue methods. Several authors have shown that digital pre-operative templating for total hip arthroplasty is an accurate and reproducible method of implant size determination (22;35;36), while others have demonstrated that digital templating is no more accurate, and perhaps less so, than templating with conventional plain films and acetate templates (20;21). The current study appears to be the first to look at the accuracy and reliability of digital templating for hip resurfacing arthroplasty. The study did not look to make comparisons to conventional radiographs and acetate templates as these are no longer available in the author’s institution. Further analysis is required to determine if analogue templating yields comparable levels of accuracy and reliability to that of digital templating for hip resurfacing.

With traditional radiography for hip arthroplasty, magnification factors are typically in the range of 115-125% (37;38). This suggests that the patient anatomy is 15-25% larger on the radiograph than true scale. Digital radiography provides the user the ability to scale the radiograph to true size and accordingly, utilize true scale implant templates. However, correctly scaling the radiograph remains a challenge for both traditional and digital radiography. A limitation to the current study is the use of a uniform correctional scaling factor for digital radiographs. An 85% scaling factor was used for all radiographs in the study. This scaling factor suggests the patient anatomy is 85% of that represented on the original radiograph, or conversely, that the original radiograph was 118% magnified. This magnification factor agrees with previous studies of standard radiographs which have shown a mean magnification of 118% (37;38). Recent work by White and Shardlow showed that the mean magnification factor in digital radiography was 97% (39). Further scaling of digital radiographs that demonstrate similar magnification factors may severely impair the accuracy of digital templating. The use of a uniform scaling factor in the current study does not correct for differences between subject size and positioning above the radiograph cartridge. The scaling factor is inversely proportional to the distance of the region of interest from the radiograph cassette and therefore smaller patients will require a larger scaling
factor. This may impact component selection in some patients by skewing implant selection toward smaller sizes. This may explain the tendency in the study for smaller, rather than larger, component selection if the correct implant size was not templated.

The current study demonstrated that digital pre-operative templating was accurate in determining the correct implant size in only half of the templates performed. Surgeons tended to undersize component selection if the correct implant size was not chosen. The risk of femoral neck notching and varus implant alignment is enhanced if a smaller femoral component is utilized. Templating reliability was variable amongst surgeons and was only fair between surgeons. This study emphasizes the need for intra-operative verification of pre-operative templating results by way of femoral neck gauge or caliper coupled with meticulous preparation of the acetabulum to ensure proper implant size selection in hip resurfacing.

### 2.3.6 References


CHAPTER 3
INTRA-OPERATIVE COMPUTER NAVIGATION

3.1 Prologue

Computer navigation is quickly becoming the gold standard of care in orthopaedics. Specifically in hip resurfacing, navigation shows promise in improving the accuracy and precision of placement of the initial femoral guidewire over conventional techniques, ultimately improving femoral head preparation. Currently, there are several types of navigation platforms 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 an alternative image-based navigation method in which a pre-operative computed tomography image is matched to the patient anatomy at the time of surgery. This provides a 3D image for planning and navigation purposes but cost and additional radiation exposure remain limits to the efficacy of CT-based navigation. Imageless computer navigation does not require pre- or intra-operative radiography, but rather registers the patient anatomy using infrared camera technology. Registration of bony landmarks and surface anatomy of the patient’s femur allow the computer system to morph or create a patient specific model. This patient specific model can be used to intra-operatively plan and navigate insertion of the femoral guidewire. Imageless navigation is not yet in wide-spread use and as such there exists limited investigation into the utility of this device for clinical use in hip resurfacing. This chapter examines the use of imageless navigation in the clinical setting and provides benchside investigation into the accuracy and reliability of this tool for placement of the initial femoral guidewire. This chapter is comprised of refereed journal articles recently published or accepted for publication (Olsen et al. 2009c, Olsen et al. 2009d, Olsen et al. 2009e, Olsen et al. 2009f).
3.2 Imageless Computer Navigation for Placement of the Femoral Component in Resurfacing Arthroplasty of the Hip

3.2.1 Abstract

The current study investigated the accuracy of femoral component placement utilizing imageless navigation in 100 consecutive Birmingham Hip Resurfacings. Pre-operative templating determined the native neck-shaft and planned implant stem-shaft angles. Stem-shaft angles (SSA) were verified post-operatively using digital AP unilateral hip radiographs. The mean neck-shaft angle determined pre-operatively was 132.7 degrees (SD 5.4, range 118-160 degrees). The planned SSA was a relative valgus alignment of 9.7 degrees (SD 2.6 degrees). The post-operative SSA differed from the planned SSA by 2.8 degrees (SD 2.0 degrees). The final SSA measured within ±5 degrees of plan in 86% of cases. No cases of neck notching or varus implant alignment occurred in the series. A learning curve was observed in the series for navigation time, however there did not exist a similar learning curve for implant placement accuracy. Navigation for hip resurfacing may afford the surgeon a reliable and accurate method of femoral component placement in hip resurfacing.

3.2.2 Introduction

The new generation of hip resurfacing presents a bone conserving alternative to total hip replacement in the young adult with acceptable short to medium-term results (1-7). Many of the problems associated with failure of the resurfacing construct in previous generations have been resolved with improved manufacturing technologies and surgical technique; however the concern of femoral neck fracture remains. Failure of the resurfacing construct has been attributed to patient characteristics such as gender, bone density, height and weight as well as mechanical factors including femoral neck notching, varus implant alignment and exposed, reamed cancellous bone (1;8-17). Several authors have suggested guidelines for optimizing implantation of the femoral component to minimize the likelihood of catastrophic failure with much of the reduction of risk factors relying on accurate preparation of the femoral head (1;8;10;14).
Successful outcomes in hip resurfacing are largely dependent on the accuracy of placement of the femoral component (14). It has been shown that a great deal of inconsistency can result between the planned implant position and the end result with use of conventional guidewire alignment instruments (18). Methods such as computer navigation have the potential to improve the accuracy of implant placement in hip resurfacing with several studies demonstrating the effectiveness of this method (19-28). There exists a paucity of clinical investigation however, into the accuracy of non-image based navigation systems in hip resurfacing. This paper describes the methods and results of intra-operative imageless computer navigation for placement of the femoral component in the first 100 consecutive navigated hip resurfacings performed at the author’s institution (St. Michael’s Hospital, Toronto, ON, Canada).

3.2.3 Methods and Materials

3.2.3.1 Patient Cohort

Between October 2005 and November 2007, 100 consecutive navigated hip resurfacings were performed by a senior surgeon (EHS). The patient cohort consisted of 77 males and 17 females. The dominant aetiology was osteoarthritis in 96 patients and avascular necrosis in 4 patients. The mean age at time of surgery was 51.3 years (SD 8.7, Range 25-82) and mean BMI was 29.5 kg/m² (SD 5.2, Range 20.4-51.9).

3.2.3.2 Pre-operative Planning

Prior to each procedure, pre-operative templating was performed to determine appropriate implant sizes and anatomical axes. Modified digital AP unilateral hip radiographs were used showing the lateral pelvis and proximal two-thirds of the femur. To determine the femoral shaft axis, a line was drawn from the most distal visible diaphyseal midpoint through a point approximating the piriformis fossa. This method of shaft axis determination is similar to methods described in the literature (29-31) and agrees with the navigation algorithm for determination of the diaphyseal axis. The neck axis was defined as a line drawn through the isthmus of the neck toward the lateral cortex intersecting the femoral shaft axis. The angle subtended by the femoral neck and shaft axes was the neck-shaft angle (NSA). Acetabular and femoral component sizes were then selected
utilizing a templating software package (EndoMap v2.01, Hectec GmbH, Niederviehbach, Germany). The femoral component was positioned in an appropriate amount of relative valgus orientation to the measured NSA (Figure 9). The angle the femoral component stem made with the femoral shaft axis was the planned stem-shaft angle (SSA). The values of the neck-shaft and stem-shaft angles were recorded for use during intra-operative navigation. The implant stem position is routinely planned to align with the medial calcar, corresponding to a SSA that is approximately 5 to 10 degrees of relative valgus. This implant angulation has been recommended in the literature and shown to strengthen the resurfacing construct (8;10;12;14;32-34).

Figure 9. Typical hip resurfacing pre-operative plan. The diaphyseal and neck axes are drawn and a digital femoral component template is positioned in a relative valgus position. The neck-shaft and stem-shaft angles are measured for use during intra-operative planning.
3.2.3.3 Operative Procedure

A standard posterolateral approach was used in all cases with patients placed in the lateral decubitus position. A lateral skin incision centered over the greater trochanter was made curving posteriorly over the hip and buttock. Soft tissue was released down to the joint capsule and a full capsulotomy was completed upon dislocation of the femur. The acetabulum was reamed in the standard fashion, with the femur retracted anterosuperiorly, and the cup was impacted in place. The femur was then maximally internally rotated and adducted elevating the femoral head out of the wound. The femoral head was prepared according to standard surgical protocol with the use of computer navigation for placement of the initial guidewire. A Birmingham Hip Resurfacing (Smith & Nephew Inc., Memphis, TN, USA), which is a hybrid resurfacing system employing a press fit acetabular cup and a cemented femoral component, was utilized in all cases.

3.2.3.4 Imageless Computer Navigation

For intra-operative surgical planning and insertion of the initial guidewire, the VectorVision imageless navigation system was used (v1.0, BrainLAB, Heimstetten, Germany). The navigation system acquires anatomic landmark and surface data to generate a patient specific model upon which intra-operative surgical planning can be conducted. The system utilizes two cameras that 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 5 mm Schanz pin is first drilled into the lesser trochanter and used to anchor the static array. Next, the medial and lateral condylar points and the piriformis fossa are acquired. These points are used by the system to delineate the diaphyseal axis. The superior head-neck junction is acquired along with clouds of points on the femoral head and the anterior, superior, posterior and inferior quadrants of the femoral neck (Figure 10). Lastly, the superior notching zone (anterosuperior neck) is registered and provides enhanced visualization of this critical area. The system calculates the NSA (or CCD, 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 NSA. The system also uses the registration data to determine the initial computed implant size and location. A computer generated, patient specific morphed model is then created and verified for accuracy.
Figure 10. Femoral Head Registration. The pointer is guided in concentric circles over the entire articular surface. Inset shows navigation planning screen.

An intra-operative planning screen was used to adjust implant size, location and angulation prior to insertion of the guidewire. A navigated drill guide was used to drill a 2.4 mm guidewire into the femoral head (Figure 11). The drill guide provides real-time feedback of guidewire position during drilling. The final guidewire location was verified using the same drill guide. Navigation time for the procedure was defined as the time between drilling of the Schanz pin into the lesser trochanter and system verification of the final guidewire position. Following verification, a stylus was inserted over the guidewire to check for notching and sufficient head resection and the remainder of the standard protocol was followed for preparation of the femoral head.
Figure 11. Guidewire drilling. The surgeon utilizes a navigated drill guide to drill the guidewire with real-time positional feedback (inset)

3.2.3.5 Post-operative Assessment

Femoral component SSA was assessed using 3 month post-operative digital AP unilateral hip radiographs. Radiographs were centered over the proximal femur and the lateral pelvis and proximal two-thirds of the femur was visible. A standard positioning protocol was observed placing the patient in the supine position with the hip extended and neutrally rotated. Three
patients were lost to follow-up at this time interval and the pre-discharge films were used for post-operative assessment. The same observer performing the pre-operative planning measured the stem-shaft angles of the femoral components. The diaphyseal axis was drawn in accordance to the pre-operative plan. A second line was drawn along the stem of the implant toward the lateral cortex and the larger angle subtended by the two intersecting lines was the SSA (Figure 12). The SSA as verified by post-operative radiograph was considered acceptable if it did not exceed 5 degrees of varus relative to the planned SSA. Stem-shaft angles in excess of 5 degrees of valgus relative to the planned SSA were considered acceptable provided the implant appeared well positioned in the absence of femoral neck notching.

![Figure 12. Post-operative assessment of the femoral component stem-shaft angle](image-url)
3.2.3.6 Statistical Analysis

The series was broken down into 20 discrete case intervals for analysis. The statistical software package SPSS (SPSS Inc., Chicago, IL, USA) was used to perform one-way ANOVA with Tukey post-hoc analysis comparing differences in navigation time and coronal alignment accuracy between each interval. Microsoft Excel (Microsoft Corporation, Redmond, WA, USA) was used to determine descriptive statistics for the series.

3.2.4 Results

Pre-operative templating determined a mean neck-shaft angle of 132.7 degrees (SD 5.4, Range 118-160). The average planned SSA was 9.7 degrees of relative valgus to the native NSA (SD 2.6 degrees). This value ranged from 0 to 16 degrees of relative valgus based on the native anatomy of the patient and the measured neck-shaft angle. Intra-operative verification of the guidewire position following insertion into the femoral head yielded a mean difference from the pre-operatively planned SSA of 0.9 degrees (SD 0.8 degrees, Range 0-3). This measure represents the error introduced by the surgeon during drilling of the guidewire. Comparison between the intra-operatively verified guidewire inclination and the post-operatively measured SSA showed a mean difference of 3.0 degrees (SD 2.0 degrees, Range 0-9). Due to the low degree of error in drilling of the guidewire, this difference was similar for the overall difference between the pre-operatively planned SSA and that measured on the post-operative radiographs which yielded a mean difference of 2.8 degrees (SD 2.0 degrees, Range 0-8). The final SSA was considered acceptable in all cases and measured within ±3 degrees of plan in 69% of cases and ±5 degrees of plan in 86% of cases (Figure 13). Of the remaining 14 cases, all measurements erred in valgus, of which none exceeded 8 degrees. When compared to the pre-operative NSA, the final SSA was an average of 11.7 degrees of relative valgus (SD 3.9, Range 1-22, 95% CI 10.9-12.5).

The most common femoral component implanted in females was 46 mm (Range 44-50 mm) and in males 54 mm (Range 46-60 mm). Corresponding acetabular component sizes were 52 mm (Range 50-56 mm) for females and 60 mm for males (Range 54-64 mm). There were no cases of superior cortex notching or relative varus implant alignment detected intra-operatively or on the post-operative radiographs. Three superficial wound infections occurred in the series but were
treated by a course of antibiotics and all resolved unremarkably. There were no other complications.

Figure 13. Differences between the pre-operatively planned SSA and the intra-operatively verified guidewire inclination and post-operatively assessed SSA. Positive values indicate relative valgus and negative values indicate relative varus.

The mean recorded navigation time for the entire series was 18.9 minutes (SD 7.4, Range 11-50). There was a significant difference in navigation time for the first 20 cases (mean 26.8 minutes, SD 11.4, range 13-50) when compared to the remainder of the series (mean 16.9 minutes, SD 4.1, range 11-29, p<0.002). There was a trend toward decreasing navigation time for the first three consecutive 20 case intervals in the series (Figure 14). The mean navigation time for the last 20 cases in the series was 15.8 minutes (SD 3.6, range 12-27). There were no significant
differences between the planned and post-operatively assessed SSA between the first 20 cases and the rest of the series (p>0.562) (Figure 14).

![Navigation learning curve](image)

**Figure 14.** Navigation learning curve. Top curve illustrates the reduction in mean navigation time in the series. There was a significant decrease in time between the first 20 cases and the remainder of the series. The lower curve demonstrates the accuracy of the final femoral component SSA

### 3.2.5 Discussion

Hip resurfacing is again gaining popularity as a viable alternative to total hip arthroplasty. As this form of joint replacement increases in widespread use, it is essential to adhere to strict guidelines in patient selection and surgical technique to ensure its continued success. Femoral
neck fracture remains the most common cause for revision in hip resurfacing (35) with femoral neck notching and varus implant alignment identified as major mechanical precursors to fracture (1;8-17). Recent work has suggested that computer navigation for hip resurfacing may reduce the incidence of femoral head malpreparation and improve femoral component placement accuracy while reducing the learning curve and the incidence of outliers (18;22-28;36). Using cadavers, Davis et al. showed that imageless navigation provided a range of error of almost half that of conventional instrumentation (8 versus 15 degrees) in placement of the initial guidewire (18). They also showed that the use of a conventional jig placed guidewires in varus position relative to the planned SSA in all specimens. In a similar cadaveric study, Hodgson et al. demonstrated that navigation provided markedly better repeatability in coronal alignment, compared to conventional instrumentation, independent of surgeon experience (23). Utilizing a cohort of 20 inexperienced medical students, Cobb et al. assessed the accuracy of guidewire placement in synthetic femurs with the use of conventional jigs, CT-based pre-operative planning and CT-based intra-operative navigation (36). The range of error for placement of the guidewire using conventional instrumentation was 23 degrees, with a similar result achieved for CT-based pre-operative planning, while CT-based navigation yielded the lowest degree of error with only 7 degrees. The study noted that not only was navigation more accurate but participants using navigation were able to quickly achieve an expert level of accuracy indicating a reduction in the length of the learning curve associated with hip resurfacing.

Although there remains minimal clinical evidence to date on the accuracy of placement of the femoral component utilizing imageless computer navigation, several recent studies have demonstrated promising results over conventional instrumentation (21;25;27;28). Resubal et al. showed that in 45 navigated hip resurfacings, the range of error from the planned SSA was within ±5 degrees in all cases, compared with only 76% (100 of 131 hips) falling within this range of error using conventional jigs (25). They also noted that notching was avoided in the navigated group while occurring 3 times in the non-navigated group. Similarly, Ganapathi et al. showed that in 51 consecutive navigated hip resurfacings, the range of error from the planned SSA did not exceed ±5 degrees, while within 88 consecutive hip resurfacings performed by standard jig, only 67% fell within this range (21). Again, notching was avoided in the navigated group while occurring 4 times in the conventional group.
The current study using navigation showed a range of error from the planned SSA of 13 degrees (5 degrees of relative varus to 8 degrees of relative valgus) while also avoiding femoral neck notching. Eighty-six percent of cases fell within $\pm 5$ degrees of plan while 14% erred in greater than 5 degrees of relative valgus. This result exceeds those of similar studies, however, the cohort in the current study is the largest reported in the literature and may provide a more realistic indication of the variability that may be encountered clinically. The pre-operative planning methodology for estimation of the diaphyseal and neck axes follows those described in the literature (29-31;37;38) and specifically, an attempt was made to harmonize the estimation of the anatomical axes to the computer algorithm which estimates these axes based on anatomical landmark selection and surface registration. It is important that the pre-operative plan be as accurate as possible in order to closely agree to the data obtained intra-operatively and thus yield accurate insertion of the initial guidewire.

The phenomenon of post-operatively assessed SSAs exceeding pre-operatively planned SSAs by greater than 5 degrees in the current study may be the result of patient malposition during radiograph acquisition combined with variation in anatomic landmark registration. During registration, the two epicondylar points and the piriformis fossa point are used to delineate the diaphyseal axis. Deviation of the registered diaphyseal axis from that drawn on the pre-operative X-ray most-likely contributes a degree of error when drilling the guidewire using the pre-operatively planned SSA. If the femur position is identical between the pre- and post-operative radiographs, it is felt that this error contributes to the spread of SSAs observed post-operatively. If there is deviation in femur position between the pre- and post-operative radiographs, this can compound the error. As a result of the degenerative condition of the hip common to osteoarthritis, the patient may not be able to adequately internally rotate in order to reduce the effect of external rotation and femoral neck anteversion. Several months post-operatively, however, the patient may be able to fully neutralize femoral neck anteversion with an internally rotated leg giving a better representation of the true anatomy. If this is the case, the pre-operatively assessed NSA and planned SSA will be an overestimate and the post-operative SSA will then be greater than expected. In a comparable navigated hip resurfacing series, Romanowski et al. noted a similar phenomenon of elevated SSAs as measured by post-operative radiograph compared to intra-operative guidewire verification (26). They also attributed this
phenomenon to a possible discrepancy between intra-operative anatomic landmark registration and assessment by AP radiograph.

Despite the presence of this discrepancy, this clinical series of navigated hip resurfacings demonstrates the accuracy of this method in achieving the desired femoral component position within an acceptable range of error while avoiding preparatory errors typical of the procedure. On average, the difference between the planned and final SSA was 2.8 degrees which is felt to be an acceptable degree of error considering that an average of almost 10 degrees of relative valgus was planned for. Furthermore, there were no cases in which the final SSA was more than 5 degrees of varus compared to the planned SSA and in 79% of cases, the final measured SSA was equal to or more valgus than the planned SSA.

The data collected for navigation time demonstrates the learning curve in the series. There was a significant improvement in navigation time between the first 20 cases and the remainder of the series. There appeared to be a trend toward decreasing navigation time for the first three consecutive 20 case intervals. This navigation time improvement appeared to level off after approximately 60 navigated hip resurfacings. Within the first 20-case interval, the initial guidewire was repositioned twice following placement verification with the manual stylus. This helped contribute to the increased navigation times experienced initially. Secondary pin positioning was conducted using a parallel drill guide from the standard BHR instrument tray followed by verification of pin alignment via the navigation system. No further secondary pin repositioning was required in the remainder of the series.

Of greater significance in the learning curve evaluation was the absence of a significant improvement in coronal alignment accuracy of the femoral component. There were no significant differences between the planned and final stem-shaft angles throughout any portion of the series. This suggests that while there may be a learning curve for registration technique, there does not appear to be a parallel learning curve for overall implant placement accuracy. This finding is supported by the work of Cobb et al. who showed that a high level of accuracy in placement of the initial guidewire can be achieved even for novice users on their first attempt utilizing navigation (36). The author’s institution is a teaching hospital and as such a number of surgical fellows and trainees participated in the registration process throughout the duration of the series. Thus, the navigation time measured demonstrates the experiences of several novice
users to imageless navigation for hip resurfacing as well as for surgeons more experienced in navigation.

There is much debate as to the ideal placement of the femoral component as various authors have made several suggestions as to the optimal component alignment (1;10-12;14). The author routinely plans between 5 and 10 degrees of relative valgus to the native neck-shaft angle. This figure is supported by both clinical and biomechanical analyses (32-34). Post-operative femoral neck fractures most frequently occur within the first several months following surgery (1;8;11;15). There were no cases of neck fracture to report in the follow-up period of 3 to 30 months in this series. As neck fracture typically occurs in only 1-2% of cases (1;8;15;17), this short-term evaluation does not serve as a conclusive indication of the success of resurfacing utilizing navigation but rather provides support for the merits of navigation in facilitating optimal preparation of the femoral head and thus reducing the risk of post-operative neck fracture. Further long-term follow-up is needed in this series to determine the true success of this procedure employing navigation.

The authors identify several limitations to the current study. Pre-operative planning and post-operative radiographic measurements were performed by a single observer. Assessment by a single observer may introduce measurement error, however post-operative SSA measurement has been shown to be a very repeatable metric with a degree of error in measurement of 1.5 degrees (39). In addition, three post-operative measurements were conducted on pre-discharge films. Patient malpositioning is more likely during these early time interval radiographs, and while a positioning protocol was utilized in obtaining all post-operative radiographs, measuring component angulation from these anteroposterior radiographs remains a limitation. Also, the current study only considered implant alignment as measured in the coronal plane, thus limiting the conclusions that can be drawn. The use of digital AP unilateral hip radiographs has been demonstrated to be a reliable method for assessment of postoperative stem-shaft angle in hip resurfacing (39) but the same has not been demonstrated for lateral hip radiographs in the assessment of femoral component version. While femoral component version in navigated hip resurfacing has been assessed by lateral radiographs in the clinical setting (25), to the author’s knowledge, there have been no studies investigating the reliability of single and multiple observer version assessment. Moreover, there have been no studies examining the impact of femoral rotation and patient malposition on hip resurfacing implant alignment projection by
lateral radiograph. As such, this parameter has not yet been quantified in this series. Further work is required to establish a repeatable method of version assessment by lateral radiographs in order to better support the benefit of imageless computer navigation in placement of the femoral component in the transverse plane of the femoral neck.

3.2.6 Conclusion

Computer navigation for placement of the initial guidewire in hip resurfacing has been shown to be more accurate than conventional mechanical jigs (18;21;23-25;28). In the current clinical series, there were no cases of femoral neck notching nor varus implant alignment detected post-operatively. Avoiding these fracture precursors is vital in ensuring the short- to medium-term success of the resurfacing construct. Imageless computer navigation shows promise in optimizing preparation of the femoral head and reducing the introduction of mechanical preparatory factors that predispose to femoral neck fracture.

3.2.7 References


3.3 Computer Navigated Hip Resurfacing for Patients with Abnormal Femoral Anatomy

3.3.1 Abstract

Hip resurfacing is a technically demanding alternative to total hip arthroplasty. The use of traditional jigs for placement of the femoral guidewire can lead to preparatory errors which may predispose the resurfacing construct to premature failure. Computer navigation is a tool that can be used to minimize the incidence of femoral head malpreparation and improve the accuracy of component placement. Computer navigation not only shows promise in routine cases of hip resurfacing but also those cases that are technically challenging. The current study demonstrates the utility of imageless computer navigation in placement of the femoral component in patients presenting with abnormal femoral anatomy.

3.3.2 Introduction

Hip resurfacing arthroplasty continues to show promise as an alternative to total hip replacement in the young, active adult. The aim of the procedure is to preserve femoral bone stock and recreate the native anatomy of the hip. Some of the challenges faced in previous generations of this form of arthroplasty remain including femoral neck fracture and implant loosening (1-3). Optimal preparation of the femoral head is strongly encouraged as a means to minimize the occurrence of femoral implant failure by avoiding iatrogenic mechanical factors such as femoral neck notching, varus implant alignment and avoidance of exposed, reamed cancellous bone (4-6).

Hip resurfacing has been described as a technically demanding procedure and patient outcomes can suffer greatly from inaccurate and poorly prepared bone stock (7). The difficulty of the procedure increases greatly for patients who present with abnormal hip anatomy. Several authors have shown relative success in hip resurfacing for patients exhibiting childhood disorders including developmental dysplasia of the hip, slipped capital femoral epiphysis and Legg-Calvé-Perthes disease (8;9) while others have shown disappointing results specifically in the placement and longevity of the femoral component in such cases (10). Few have commented on resurfacing
for the case in which abnormal proximal femoral geometry exists as the result of fracture or osteotomy repair, specifically with hardware remaining in situ (11).

Computer assisted surgery is gaining popularity in hip resurfacing arthroplasty and shows potential as a means of increasing the accuracy of bone preparation and implant placement (12-16). Imageless computer navigation for hip resurfacing is not yet widely employed but its advantages over traditional mechanical means have been described (17-23). Computer navigation not only shows promise in routine cases of hip resurfacing but also those cases that are technically demanding. The current study demonstrates the utility of imageless computer navigation in placement of the femoral hip resurfacing component in patients exhibiting abnormal femoral anatomy.

3.3.3 Methods and Materials

Between October 2005 and September 2008, 165 consecutive navigated hip resurfacings were performed by a senior surgeon (EHS). Of this consecutive series, 7 patients presented with extra-articular deformity or retained hardware that would make a total hip arthroplasty difficult. The study cohort consisted of 6 males and 1 female with a mean age of 51 years (range 26-82). The mean BMI was 34.7 kg/m² (range 26.2 to 44.5). The primary diagnosis was osteoarthritis in 5 patients and avascular necrosis in 2 patients. One patient had a severe varus deformity of the proximal femur (Figure 15), three patients presented with bladeplates for proximal femoral osteotomy and fracture fixation (Figure 16), 1 patient had a tantalum AVN rod (Figure 17), and the femoral necks of 2 patients contained threaded pins for previous neck fracture (Figure 18). A standard posterolateral approach was used in all cases with implantation of a Birmingham Hip Resurfacing (Smith & Nephew Inc., Memphis, TN, USA), which is a hybrid resurfacing system employing a press fit acetabular cup and a cemented femoral component. For statistical analysis, patients within the study cohort were matched to patients within the hip resurfacing series in a 2 to 1 ratio for primary diagnosis, sex, age, and BMI. The mean age of the matched cohort was 51 years (range 26-73) and mean BMI was 33.7 kg/m² (range 21.3 to 45.9).
Figure 15. Patient with severe varus deformity of right hip resulting from previous comminuted femoral shaft fracture: A) pre-op; B) pre-op plan; C) 3-month post-op SSA verification

3.3.3.1 Pre-operative Planning

Pre-operative planning was performed using modified digital AP unilateral hip radiographs displaying the lateral pelvis and proximal two thirds of the femur. The radiographs were scaled and templated for femoral and acetabular component sizes. The templated femoral component was positioned in a suitable valgus orientation and the angle the component stem made with the diaphyseal axis was the stem-shaft angle (SSA). The planned SSA was recorded for use in the navigation process. Valgus orientation of the femoral component is recommended in the literature (4;6;7;24) and has been shown to mechanically strengthen the resurfacing construct (25-29). Approximately 5 to 10 degrees of valgus alignment relative to the native neck-shaft angle is routinely planned or in the cases of retained hardware, an acceptable alignment permitted by the hardware in situ. Lateral radiographs were used to help gauge the position of the prostheses in the neck and in the cases of retained hardware in the femoral head and neck, the relative position of
the stem of the resurfacing component. Post-operatively, 3-month AP unilateral hip and lateral hip radiographs were used to assess component position.

Figure 16. Patient with previous proximal femoral fracture fixed with a blade plate: A) pre-op; B) post-op AP radiograph, inset: arrow shows edge of bladeplate on cylindrically reamed femoral head; C) post-op lateral radiograph showing femoral component well aligned in femoral neck

3.3.3.2 Imageless Computer Navigation

The BrainLAB VectorVision SR 1.0 (BrainLAB, Heimstetten, Germany) imageless computer navigation unit was used in all cases for intra-operative planning and guidewire insertion (30). Patient anatomy was registered according to the requirements of the navigation system. Following registration, a patient specific morphed model was generated and used to plan the implant position. A hand-held drill guide was used to guide the drilling of the initial guidewire. Upon insertion, the guidewire position was verified by the navigation system. A stylus was inserted over the guidewire to check for notching and proper resection of the femoral head. The femoral head was
subsequently prepared following the standard surgical protocol. The time for navigation was recorded for each case.

![Image](image1.png)

**Figure 17.** Patient with Tantalum AVN rod *in situ*: A) pre-op; B) pre-op plan; C) post-op, inset: arrow shows tip of AVN rod on chamfered edge of femoral head adjacent central canal

### 3.3.4 Results

There were no intra- or post-operative surgical complications to report. Upon examination of 3-month post-operative AP and lateral radiographs, femoral components appeared well positioned in the coronal and sagittal planes with no signs of femoral neck notching. The mean deviation of the post-operatively assessed SSA from the pre-operative plan was 0.6 degrees (SD 3.5, range -5 to 6 degrees). The mean navigation time was 18 minutes (SD 6, range 11 to 27 minutes). The mean postoperative SSA error and navigation time for the matched patient cohort was 1.6 degrees (SD 2.2, range 1 to 6 degrees) and 18.6 minutes (SD 9.9, range 10 to 50 minutes), respectively. There
were no significant differences between patients in the study cohort and matched subjects with respect to SSA error (p=0.464) and navigation time (p=0.904).

![Images of patient with retained threaded pins for previous femoral neck fracture: A) pre-op; B) pre-op plan; C) post-op AP radiograph](image)

Figure 18. Patient with retained threaded pins for previous femoral neck fracture: A) pre-op; B) pre-op plan; C) post-op AP radiograph

3.3.5 Discussion

The use of computer assisted surgical techniques is growing in popularity, specifically in hip resurfacing arthroplasty, providing the benefits of increased accuracy and a reduced learning curve (14;17;20). Computer navigation for placement of the femoral component reduces much of the inaccuracy introduced by the surgeon with the use of conventional mechanical alignment instruments by eliminating the error inherent in visual alignment and replacing it with absolute measures of implant position (17-19;21-23). In addition, imageless navigation does not require a lateral cortex pin as is required with several mechanical alignment jigs. Insertion of a lateral pin may be difficult in cases in which hardware is fixed to the lateral cortex of the femur.
Hip resurfacing presents an attractive alternative to conventional total hip replacement for patients with proximal femoral deformity or retained hardware. Total hip arthroplasty in conjunction with corrective osteotomy has shown limited success. Papagelopoulos et al. reported on 20 primary conventional total hip arthroplasties all requiring simultaneous corrective osteotomy for proximal femoral deformity (31). Half of the patients experienced complications including intra-operative femoral fracture, dislocation, osteotomy non-union, aseptic implant loosening and instability with a subsequent 30% re-operation rate. Others have shown varying success with primary total hip replacement in conjunction with osteotomy or hardware removal (32-34), however lengthy osteotomy union and healing times and high rates of complication appear consistent with this form of complex primary hip arthroplasty.

For appropriate patients, hip resurfacing may eliminate the need for corrective femoral osteotomy or the removal of proximal femoral hardware. Mont et al. performed primary metal-on-metal hip resurfacing in 15 patients (17 hips) presenting with proximal femoral deformity or retained hardware (11). At a mean follow-up time of 3 years, 14 patients (16 hips) were doing well both clinically and radiographically with only one patient requiring revision for a femoral neck fracture and subsequent implant loosening. In a similar fashion, the current study demonstrates the efficacy of hip resurfacing for patients with abnormal femoral anatomy, specifically with the use of imageless computer navigation for placement of the femoral component. Complex, primary hip resurfacing is a viable option for patients with abnormal femoral anatomy or retained proximal femoral hardware and the accuracy of placement of the femoral component is enhanced with computer navigation. The limitation of hip resurfacing in these complex cases however, is the requirement for appropriate femoral head and neck geometry on which to seat the femoral component.

Imageless computer navigation for hip resurfacing can be an effective tool to aid the surgeon in femoral head preparation. However, it is imperative that a prudent pre-operative plan be carried out prior to intra-operative use of navigation to ensure accurate and well positioned implants. Patient selection in hip resurfacing is critical and the use of computer navigation cannot correct for poor patient selection. In addition, poorly selected landmarks and careless registration can remove much of the benefit of navigation. Navigation can, however, increase the accuracy of implant placement and reduce the incidence of mechanical preparatory error if utilized properly. The current study demonstrates the merit of imageless computer navigation for placement of the
femoral component in difficult cases of hip resurfacing arthroplasty. Additional follow-up of patients receiving peri-prosthetic hip resurfacing and hip resurfacing for malformed proximal femoral anatomy is warranted to determine the efficacy of this arthroplasty intervention in this patient population.

3.3.6 References


3.4 A Comparison of Conventional Guidewire Alignment Jigs with Imageless Computer Navigation in Hip Resurfacing Arthroplasty

3.4.1 Abstract

The purpose of the current investigation was to determine the accuracy and precision in placement of the initial femoral guidewire with conventional alignment jigs in hip resurfacing and to compare results to imageless computer navigation. Five commercially available jigs were obtained [2 lateral pin (LP); 2 neck centering (NC); 1 head planing (HP)]. Four surgeons used each jig and navigation 3 times to insert a guidewire in 10 degrees of relative valgus and neutral version alignment into individual synthetic femurs. A single surgeon then used each jig 3 times to align the initial guidewire in 10 degrees of relative valgus and neutral version alignment in each of 10 human cadaveric femora. Radiographs of the synthetic and human femurs were taken to assess guidewire inclination and version. Navigation provided ranges of error in coronal guidewire alignment up to 8 times less than conventional jigs but provided similar ranges of error in guidewire version. In both arms of the study there were significant differences in coronal alignment accuracy between the two neck centering jigs. Next to navigation, a lateral pin jig provided the most accurate coronal placement of the initial guidewire while a neck centering jig provided the most precise coronal guidewire placement. Navigation provided similar results to conventional jigs in guidewire version accuracy and precision. Correct alignment of the initial femoral guidewire is vital in avoiding malpreparation of the femoral head. Choice of alignment device may influence the accuracy and precision of guidewire insertion, ultimately impacting femoral component placement. Imageless computer navigation provided accurate and precise coronal alignment of the initial femoral guidewire, superior to that of conventional instrumentation, but performed similarly to conventional jigs in femoral guidewire version. The results of the current study may aid surgeons in the selection of alignment instruments for placement of the initial femoral guidewire in hip resurfacing.
3.4.2 Introduction

Hip resurfacing is gaining popularity as a bone conserving alternative to total hip arthroplasty in the young and active adult with degenerative hip disease. Much of the success of the hip resurfacing procedure relies on optimal implantation of the prostheses (1-3). Poor placement of the acetabular and femoral components has been associated with femoral neck fracture, implant loosening, femoro-acetabular impingement, excessive implant wear and increased blood metal ion levels (4-16). In hip resurfacing, the acetabular component is implanted in much the same fashion as an uncemented, press-fit total hip arthroplasty. However, implantation of the femoral component is unique to hip resurfacing, presenting its own distinct challenges.

Commonly, manual mechanical alignment jigs are used to insert the initial guidewire into the femoral head and neck. This technique relies on surgeon visualization for guidewire alignment and insertion position. The use of conventional jigs may lead to malinserted femoral guidewires which may ultimately lead to malprepared femoral heads (17-20). Imageless computer navigation shows promise in minimizing femoral head malpreparation and increasing the accuracy and precision with which the guidewire is inserted (21-23), specifically when compared to conventional instrumentation (17-20;24-27). However, the cost of current hip resurfacing navigation systems presents a major limitation to its widespread use (19).

There exist numerous manual alignment jigs each employing different methods for alignment of the initial femoral guidewire in hip resurfacing. However, there is no clear indication as to which alignment methods or jig characteristics provide the user with the most optimal guidewire placement. Furthermore, there appear to be no studies that have compared the accuracy and precision of the various guidewire alignment jigs presently available to each other and to that of computer navigation. The purpose of the current investigation was to determine the accuracy and precision in placement of the initial femoral guidewire with conventional alignment jigs and to compare results to imageless computer navigation.

3.4.3 Methods and Materials

Five commercially available jigs were obtained [2 lateral pin (LP); 2 neck centering (NC); 1 head planing (HP)] (Figure 19). The study utilized 72 large left synthetic femora and ten dried,
denuded, adult left cadaveric femora (Pacific Research Laboratories, Vashon, WA, USA). A draped foam hip model (Model 1516, Pacific Research Laboratories, Vashon, WA, USA) with a posterolateral approach was used to simulate the operative environment (Figure 19F). Digital anteroposterior (AP) and lateral radiographs of the synthetic and human femora were taken to assess guidewire angulation.

Four fellowship trained orthopaedic surgeons participated in the study. Prior to the study, representatives from the manufacturers of the alignment jigs were invited in to instruct the four surgeons participating in the study on the use of each jig. During the in-service demonstration, each surgeon used each jig to drill one guidewire into a synthetic foam femur. Surgeons received no further instruction for jig use. Surgeons were provided with the manufacturer’s suggested surgical protocol for jig use and were permitted to consult the protocol during the study.

3.4.3.1 Conventional Guidewire Alignment Jigs

3.4.3.1.1 Lateral Pin Jigs

The two lateral pin jigs each utilized a short pin that inserted into the lateral cortex of the femur. Using digital templating software (EndoMap v2.01, Hectec GmbH, Niederviehbach, Germany), surgeons templated pre-operative digital AP unilateral hip radiographs of the synthetic and cadaveric femora for the position of the pin on the lateral cortex. This position was defined as the vertical distance from the tip of the greater trochanter to the intersection of the lateral cortex and a line drawn along the center of the planned implant stem. For synthetic femurs, a uniform size 46 mm implant was templated. For cadaveric femora, an implant size was selected such that a relative 10 degree valgus orientation could be achieved without notching of the superior neck. To avoid magnification errors, a full scale magnification was used as femurs were placed directly on the radiograph cassette with the plane of the femoral neck parallel to the cassette.
Figure 19. A) Lateral Pin Jig 1 (LP1); B) Lateral Pin Jig 2 (LP2); C) Neck Centering Jig 1 (NC1); D) Neck Centering Jig 2 (NC2); E) Head Planing Jig (HP); F) Foam model of left hip with cadaveric femur
The lateral pin was inserted in the location determined by templating. The long arm of each jig was hooked onto the pin and the cannulated rod was placed on the femoral head. Jig LP1 had an adjustment screw on the arm of the jig to facilitate easy placement of the jig onto the lateral pin while the femur was internally rotated. A notching stylus, sized to the femoral component size chosen, was rotated around the femoral neck to check for notching. The position of the cannulated rod on the femoral head was adjusted until the stylus could swing freely around the femoral neck. Jig LP2 had a screw that could make small version alignment alterations without repositioning the cannulated rod on the femoral head. The femoral guidewire was then drilled and the stylus was used again to verify proper insertion.

3.4.3.1.2 Neck Centering Jigs

Jig NC1 had two arms that fixed directly to the femoral neck, one superiorly and one inferiorly. The inferior arm was adjustable in length to facilitate valgus orientation of the jig. Once the arms were fixed in place, the jig was visually aligned and a cannulated rod was tightened down onto the femoral head. The femoral guidewire was then drilled. Notch checking was performed once the guidewire was inserted. If notching was detected, the guidewire could be moved using a parallel drill guide. Jig NC2 did not fix to the neck but clamped around it. A head centering jig was then attached to the neck clamp ring securing it in place. Two long orientation pins could be inserted into the centering jig and used to visually align the jig in the coronal and sagittal planes. The femoral guidewire was then drilled and a stylus was placed over the guidewire to check for neck notching.

3.4.3.1.3 Head Planing Jig

The head planing jig required an initial plane of the femoral head to position the base of the alignment jig. An initial short guidewire was drilled into the femoral head aimed to align approximately with the center of the femoral neck in the coronal and sagittal planes. The plane cutter was passed over the guidewire and the medial aspect of the head was initially planed a depth of approximately 6 mm. The base was impacted in place and the assembled centering jig was attached. The cannulated rod of the centering jig could freely rotate to obtain the necessary
coronal and version alignment for the initial guidewire. The cannulated rod was then locked in place. With the guidewire alignment determined, the jig could slide on the base craniocaudally and anteroposteriorly to obtain the initial entry point. The base was subsequently locked in place and a stylus was used to detect for notching. The jig was repositioned until the stylus was free to rotate around the neck. The initial guidewire was then inserted followed by a final check with the stylus.

3.4.3.1.4 Imageless Computer Navigation

The VectorVision SR 1.0 imageless computer navigation system (BrainLAB, Heimstetten, Germany) was used in the study. The technique for patient registration and surgical planning has been described elsewhere (22). Briefly, the navigation system uses an infrared camera and array system to intra-operatively register the patient’s femoral anatomy. The computer creates a patient specific morphed model on which planning of implant size and position can be carried out. Once a plan has been accepted, the initial femoral guidewire is inserted into the femoral head using a navigated drill guide. Upon insertion of the guidewire, the system can verify its final angulation in situ. The remainder of the standard surgical protocol is followed for preparation of the femoral head.

3.4.3.2 Synthetic Femora Study Design

Four surgeons used each jig 3 times to drill a guidewire in 10 degrees of relative valgus alignment and neutral version into individual synthetic femurs situated within the foam hip model. The native neck-shaft angle of the synthetic femurs was 120 degrees with native femoral neck anteversion of 8 degrees. The order of jig use was randomized for each surgeon and for each guidewire insertion. Jigs were disassembled between each use. Each surgeon used imageless navigation to drill three consecutive guidewires into individual synthetic femurs following the completion of jig use. Surgeons were timed for each use of the jigs and navigation. Guidewire insertion time for the jigs was defined as the time to assemble each jig, fix it to the femur, align and drill the femoral guidewire. For Navigation, the guidewire insertion time was defined as the
time to insert the Shanz pin into the Lesser Trochanter, register the femur, plan the position of the implant, drill and verify the femoral guidewire.

3.4.3.3 Cadaveric Femora Study Design

A single surgeon used each jig 3 times to align, but not insert, the initial guidewire in 10 degrees of relative valgus alignment and neutral version in each of 10 dried femora. A single observer determined the native neck-shaft angle of each femur by AP radiograph and a second observer repeated the measurements. Each femur was registered using navigation prior to commencing jig use. The order of jig use was randomized between each guidewire alignment iteration, however, the head planing jig was used last as this required removal of femoral head bone and would alter the use of the other jigs. Jigs were disassembled between each use. Guidewire alignment for each use of the jig was verified using the navigation system. Following each use of a jig, the navigation drill guide was placed over the jig aligned guidewire and the computer then verified the inclination and version of the guidewire. The surgeon was blind to the verification result of each guidewire. Following jig use, a single guidewire was inserted into each cadaveric femur using navigation.

3.4.3.4 Guidewire Alignment Assessment

To assess coronal guidewire alignment, digital AP radiographs of the synthetic and cadaveric femora were taken with the femoral neck positioned parallel to the radiograph cassette. The guidewire alignment angle was measured in a similar fashion to the standard stem-shaft angle (SSA) assessment in hip resurfacing (28). The angle subtended by the intersection of the line drawn along the guidewire and the diaphyseal axis was the coronal guidewire alignment angle. Guidewire version was assessed by using a digital lateral radiograph in which the thinnest portion of the neck was projected onto the radiograph cassette. A line was drawn between the anterior and posterior cortices at the isthmus of the neck. Two parallel lines were drawn 5 mm medial and 5 mm lateral to the isthmus line. The midpoints of these two lines were connected and represented the native femoral neck axis. The implant stem-neck angle (SNA) was represented by the angle subtended by the guidewire and the femoral neck axis. A single observer measured femoral guidewire coronal and version alignment in the synthetic and
cadaveric femora. A second observer repeated the guidewire version alignment measurements performed on the cadaveric femora to determine the repeatability of this measurement method.

3.4.3.5 Statistical Analysis

For determination of descriptive statistics and for analysis of differences between alignment methods, surgeons and femurs, Excel and the statistical software package SPSS16 (SPSS Inc., Chicago, IL, USA) were used. Alignment method accuracy was defined as the mean error from the planned relative 10 degree SSA and neutral SNA as measured by radiograph. Repeated measures analysis of variance with Tukey post-hoc analysis was performed comparing the differences in alignment error between alignment methods and surgeons for the synthetic femurs and between alignment methods and femurs for the cadaveric femora. Alignment method precision was defined as the average standard deviation across surgeons for synthetic femora and the average standard deviation across femurs for the cadaveric femora. To evaluate jig precision, a Kruskall-Wallis analysis of ranks was used comparing average standard deviations for alignment method error with Mann-Whitney U post-hoc tests to determine differences between individual alignment methods. The time taken to use each alignment device was evaluated in a similar fashion. A p value of 0.05 was considered significant. An Intraclass Correlation Coefficient (ICC) was calculated to determine the level of repeatability between the two observers who measured both the native neck-shaft angle and guidewire version in the cadaveric femora. A two-way, random effects model measuring single measure reliability was used with absolute measurement agreement considered in the statistical model.

3.4.4 Results

3.4.4.1 Synthetic Femora

Alignment method accuracy and precision are summarized in Table 2. The only significant difference in coronal inclination accuracy occurred between the two Neck Centering jigs (p=0.028). With respect to version accuracy, jig LP1 produced a mean version error of 1.8 degrees retroversion (SD 5.9) while the other jigs and Navigation erred in anteversion (0.3-4.9 degrees, SD
and this was significantly different compared to jigs LP2, HP and Navigation (p<0.049). Compared to Navigation (range 2 degrees varus to 2 degrees valgus coronal alignment error, 11 degrees ante- to 5 degrees retroversion error), the range of error for the jigs was 2 to 8 times greater in coronal inclination (Figure 20A) but similar in version (Figure 20B). There was a significant difference in coronal inclination accuracy obtained between surgeons (p<0.011) but there was no difference between surgeons in version accuracy (p>0.156).

Table 2. Guidewire Placement Accuracy and Precision

<table>
<thead>
<tr>
<th>Alignment Method</th>
<th>Coronal Inclination Accuracy (SD)</th>
<th>Version Accuracy (SD)</th>
<th>Coronal Inclination Precision (SD)</th>
<th>Version Precision (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Synthetic</td>
<td>Cadaveric</td>
<td>Synthetic</td>
<td>Cadaveric</td>
</tr>
<tr>
<td>LP1</td>
<td>-0.1 (4.5)</td>
<td>0.3 (2.8)</td>
<td>1.8 (5.9)</td>
<td>1.5 (3.2)</td>
</tr>
<tr>
<td>LF2</td>
<td>-1.8 (5.0)</td>
<td>-1.6 (2.3)</td>
<td>-4.1 (4.2)</td>
<td>-1.6 (3.0)</td>
</tr>
<tr>
<td>NC1</td>
<td>3.4 (5.7)</td>
<td>2.1 (3.1)</td>
<td>-1.0 (6.5)</td>
<td>-1.1 (3.5)</td>
</tr>
<tr>
<td>NC2</td>
<td>-4.7 (2.4)</td>
<td>-1.9 (2.0)</td>
<td>-0.3 (3.8)</td>
<td>-1.8 (2.6)</td>
</tr>
<tr>
<td>HP</td>
<td>2.4 (9.2)</td>
<td>-1.3 (5.3)</td>
<td>-4.9 (6.2)</td>
<td>-0.4 (3.6)</td>
</tr>
<tr>
<td>Navigation</td>
<td>0.2 (1.5)</td>
<td>-1.1</td>
<td>-4.2 (6.3)</td>
<td>0.1</td>
</tr>
</tbody>
</table>

*Values in degrees, positive values denote valgus and retroversion. LP1: Lateral Pin jig 1; LP2: Lateral Pin jig 2; NC1: Neck Centering jig 1; NC2: Neck Centering jig 2; HP: Head Planing jig

With regard to guidewire inclination precision, Navigation (1.3 degrees, SD 0.5) was more precise than all alignment jigs (1.3-7.2 degrees, SD 0.3-2.5) and this was significant compared to jigs LP1 and HP (p<0.026). Jig HP was the least precise alignment device (7.2 degrees, SD 2.3) and this was significant compared to the two Lateral Pin jigs, jig NC2 and Navigation (1.3-3.2 degrees, SD 0.3-1.1, p<0.021). There was no significant difference in guidewire version precision between the alignment method groups (p=0.299).
Figure 20. Box and Whisker plot of synthetic guidewire alignment error for inclination (A) and version (B). Positive values represent valgus and retroversion.
The mean guidewire insertion times for the alignment methods are shown in Figure 21. The Head Planing jig took significantly longer to use than the rest of the jigs and Navigation (mean 14.1 minutes, SD 6.5, p<0.001). Neck Centering jigs took the shortest amount of time with Lateral Pin jigs (p<0.006) and Navigation (p<0.001) both taking significantly longer to insert the guidewire. There were no differences in guidewire insertion time between the two Lateral Pin jigs (p=0.160) or between the two Neck Centering jigs (p=0.887). There was no significant difference in guidewire insertion time between surgeons in the study (p=0.913).

![Figure 21. Alignment method time. Neck Centering jigs required the shortest amount of time to insert the initial guidewire (p<0.006) while the Head Planing jig required the most time (p<0.001). There was no statistical difference between Neck Centering jigs or Lateral Pin jigs (p>0.160)
3.4.4.2 Cadaveric Femora

There were significant differences in coronal inclination accuracy between the Lateral Pin jigs (p=0.027) and between the Neck Centering jigs (p<0.001) (Table 2). Jig NC1 tended to place guidewires in valgus orientation compared to plan (mean 2.1 degrees, SD 3.1) and this was significant compared to all other jigs (1.9 degrees varus to 0.3 degrees valgus, SD 2.0-5.3, p<0.049). Analysis of version accuracy showed that jig LP1 produced a mean version error of 1.5 degrees retroversion (SD 3.2) which was significantly different compared to the other jigs which tended to err in anteversion (0.4-1.8 degrees, SD 2.6-3.6, p<0.010). Compared to Navigation (range 1 degree varus to 2 degrees valgus coronal alignment error, 4 degrees ante- to 4 degrees retroversion error), the range of error for the jigs was 3 to 7 times greater in coronal inclination (Figure 22A) but similar in version error (Figure 22B). Coronal inclination accuracy was not dependent on femur specimen (p>0.377), however, version accuracy was, as there were multiple differences in accuracy obtained between specimens (p<0.030). In particular, Femur 2 produced a version error of 5.5 degrees of anteversion and this was significant compared to all other femurs (p<0.002). The mean difference between the two observers in coronal neck-shaft angle measurement for the cadaveric femora was 1.1 degrees (SD 2.3) and for guidewire version measurement was 1.4 degrees (SD 1.9) with ICCs of 0.85 and 0.70, respectively. Jig HP demonstrated significantly less precision than all other jigs in coronal inclination (6.3 degrees, SD 2.2, p<0.023) (Table 2). Similar to the synthetic femur arm of the study, there was no significant difference in version precision observed between the jigs (p=0.120).
Figure 22. Box and Whisker plot of cadaveric guidewire alignment error for inclination (A) and version (B). Positive values represent valgus and retroversion.
3.4.5 Discussion

Successful outcomes in hip resurfacing are largely dependent on optimal positioning of the components and short term failure of the resurfacing construct is often attributable to femoral neck fracture. Neck fracture is frequently the result of a poorly prepared femoral head in which femoral neck notching or varus implant alignment has occurred. Computer navigation is a tool that can be used to minimize femoral head malpreparation by reducing outliers and providing quantitative means for prosthesis implantation. Navigated hip resurfacing is not yet commonplace as many surgeons rely on mechanical means for femoral guidewire alignment and insertion. However, it has been demonstrated in both clinical and benchside studies that imageless computer navigation may provide more accurate and precise placement of the initial femoral guidewire than conventional instrumentation (17-20;24-27). A major limitation in many of these comparative studies is the use of only one type of conventional jig. Numerous alignment jigs are currently available each employing unique methods of fixation and alignment and as such it is advantageous to understand the relative strengths and weaknesses of these conventional jigs and directly compare them to computer navigation.

The current study demonstrated that imageless computer navigation was superior to conventional jigs in coronal inclination accuracy and precision but fared no better in version. The findings of the current study support previous work comparing coronal femoral guidewire placement by conventional means and imageless computer navigation. Using cadavers, Davis et al. investigated coronal guidewire alignment accuracy using a conventional lateral pin jig and compared it to imageless navigation (24). They found that the lateral pin jig tended to place guidewires in varus alignment relative to the planned guidewire angle and that the range of error in placement of the initial guidewire was reduced from 15 degrees in the jig group to 8 degrees in the navigation group. Hodgson et al. also used cadavers to compare the precision of a head planing jig to that of imageless navigation and found navigation significantly more precise in coronal alignment (SD 1.2 vs. 2.8 degrees) (25). In a clinical retrospective cohort study, Resubal and Morgan used imageless navigation to achieve a stem-shaft angle accuracy of ±5 degrees of plan in 100% of cases (45 of 45) while achieving this in only 76% of cases (100 of 131) using a conventional lateral pin jig (19). Comparable results were demonstrated in a similar retrospective clinical review in which an accuracy of ±5 degrees of plan was achieved in the
computer navigated group in all cases (51 of 51) but in only 62% of non-navigated cases (55 of 88) (17).

While numerous studies have demonstrated the increased accuracy and precision of imageless navigation compared to conventional jigs in coronal implant alignment, only a few studies have investigated femoral component version. Cobb et al. compared imageless navigation to conventional instruments and CT-based navigation for placement of the initial femoral guidewire utilizing dry bone models with optimal CT-based planning (29). All three methods showed comparable accuracy, however imageless navigation exhibited the poorest precision (SD 9 degrees) compared to CT-based navigation (SD 2 degrees, p<0.001) and conventional neck centering jig instrumentation (SD 5 degrees, p=0.015). A similar finding was reported in a cadaver study in which imageless navigation (SD 4.4 degrees) was less precise than a conventional head planing jig (3.2 degrees) in version, however this difference was not significant (p=0.20) (25). In contrast, Resubal and Morgan showed that imageless navigation (SD 1.53 degrees) was significantly more precise in femoral component version than a mechanical lateral pin jig (SD 4.36 degrees, p=0.025) while demonstrating no difference in accuracy between the two methods (19). The current work supports the finding that imageless computer navigation provides similar results to conventional jigs in guidewire version accuracy while also providing a comparable level of precision. Results showed that proximal femoral morphology may have an impact on version visualization, however, no such effect was detected for coronal alignment.

Next to Navigation, jig LP1 provided the most accurate coronal alignment of the initial guidewire. This may be the result of pre-operative measurement of the pin insertion point on the lateral cortex of the femur by AP radiograph thus creating a reference position to aid in coronal alignment. However, radiograph magnification or scaling variability could lead to erroneous lateral pin insertion measurements which ultimately may impact the use of the jig and insertion of the initial guidewire. Despite the common fixation method, there existed several differences between the two lateral pin jigs. Jig LP1 tended to err in retroversion compared to jig LP2 as well as the other alignment methods in both the synthetic and cadaveric femora. Jig LP1 did not have an adjustment for guidewire version, unlike jig LP2, and thus, anterior lateral pin placement, which can lead to retroverted guidewire insertion, could not be adequately corrected. Additional drawbacks to using a lateral pin jig include the possibility of a longer incision to
accommodate pin insertion; as well, care must be taken to remove the pin from the lateral cortex of the femur upon completion of the operation.

Jig NC2 provided the most precise coronal guidewire alignment next to that of Navigation. This may be the result of the circular clamping ring used to fix the device to the femoral neck. The clamping device provided repeatable placement of the head centering jig but was limited in the degree of valgus that could be introduced on an oval shaped femoral neck and thus all guidewires in the study were inserted in varus compared to the planned stem-shaft angle of 10 degrees of relative valgus. In contrast, jig NC1 tended to place guidewires in valgus compared to plan in both arms of the study and this was significant with the cadaveric femora. Both jigs were limited in that notch checking could not be performed until after the initial guidewire had been inserted. In addition, though not necessary with the femora used in the current study, the circular clamping device of jig NC2 requires the removal of osteophytes to be properly situated on the femoral neck and failure to do so may affect the accuracy of the jig in the operative setting.

The surgeon experience with the head planing jig was unique to that of the other jigs used in the study. The initial medial head plane appeared to have a significant impact on guidewire insertion accuracy and precision. The base of the jig allowed for a fixed amount of travel to obtain the initial entry point, however, if the required entry point could not be obtained, the base of the jig required repositioning which often necessitated replaning the femoral head. This tended to increase the time taken to insert the femoral guidewire and may have resulted in the larger ranges of error in guidewire insertion accuracy and precision. The tendency for longer guidewire insertion times agrees with similar studies comparing a head planing jig and imageless navigation (25;26).

The author identifies several limitations to the current study. Guidewire insertion using synthetic and cadaveric femora situated within a foam hip model may not exactly replicate the clinical setting for hip resurfacing. The test conditions presented an optimal setting for evaluating the accuracy and reliability of conventional jig instrumentation and imageless navigation. Registration of synthetic and denuded femurs presented a best-case-scenario in which complicating factors such as proximal femoral deformity and soft tissue effects were removed. However, the testing construct aimed to simulate the exposure created by a posterolateral approach of the hip and thus yield more realistic results. Clinically, lower levels of accuracy and
precision and larger ranges of error are anticipated caused by factors such as variable patient anatomy and the presence of proximal femoral soft tissue. Secondly, a potential bias existed for the surgeon performing guidewire alignment in the cadaveric arm of the study. The surgeon had already utilized the jigs on synthetic femurs and as a result may have become more proficient in their use. However, the aim of the cadaveric portion of the study was to ascertain the effect of variable femoral morphology on the accuracy and precision of guidewire insertion using conventional instrumentation and the results demonstrated similar trends in jig error between synthetic and cadaveric femurs. Additionally, while the ICC between the two observers was acceptable for the measurement of neck-shaft angle of the cadaveric femora, it was marginally lower than that considered acceptable for the measurement of guidewire version (30). Further investigation is required to establish the best method of version assessment by lateral radiograph in hip resurfacing.

3.4.6 Conclusion

Correct alignment of the initial femoral guidewire is vital in avoiding malpreparation of the femoral head in hip resurfacing. The choice of conventional alignment device may influence the accuracy and precision of guidewire placement, ultimately impacting femoral component implantation. Imageless computer navigation provides accurate and precise coronal alignment of the initial femoral guidewire, superior to that of conventional instrumentation, but performs similarly to conventional jigs in femoral guidewire version.

3.4.7 References


3.5 Imageless Computer Navigation without Pre-operative Templating may lead to Femoral Head Malpreparation in Hip Resurfacing

3.5.1 Abstract

Computed neck-shaft angle (NSA) and femoral component size were recorded from one hundred consecutive imageless computer navigated hip resurfacings and compared to the pre-operatively measured NSA and the actual femoral component implanted. The reliability in registration output was further analyzed using 10 cadaveric femora. The mean absolute difference between measured and navigated NSA was 16.3 degrees (SD 12.4, Range 0-52). Navigation underestimated the measured NSA in 38 cases and the correct implant size in 11 cases. Registration of the cadaveric femora tended to overestimate the correct implant size and provided a low level of repeatability in computed NSA. Prudent pre-operative planning must be used in conjunction with imageless navigation as it appears that misleading information may be registered intra-operatively and could potentially lead to femoral head malpreparation.

3.5.2 Introduction

Hip resurfacing arthroplasty presents a viable alternative to total hip replacement in the young and active adult with end-stage osteoarthritis. The benefits of this form of arthroplasty include preservation of femoral bone stock and recreation of the native anatomy while the challenges of femoral neck fracture and implant loosening persist. Factors affecting implant failure that have been identified in the literature include gender, height, obesity, poor bone quality, large cystic defects, excessive femoral neck soft tissue removal, superior cortex notching, relative varus implant alignment and exposed reamed cancellous bone (1-11). The latter of these are mechanical factors introduced by the surgeon during femoral head preparation.

Conventional preparation of the femoral head is performed using mechanical jigs that fix to the proximal femur to drill the initial guidewire. The surgeon uses visual alignment of the jig to drill
the guidewire but visibility and visual error present obstacles to the accuracy of this method. Computer navigation for hip resurfacing shows promise in improving the accuracy of insertion of the initial guidewire and ultimately improving the quality of preparation of the femoral head and final implant placement (12-23). While computer navigation may be a powerful tool to minimize malpreparation of the femoral head, the use of imageless computer navigation in the absence of a thorough pre-operative template may lead to less accurately implanted components and potentially diminished surgical outcomes.

3.5.3 Methods and Materials

3.5.3.1 Clinical Series

3.5.3.1.1 Patient Cohort

Between May 2007 and September 2008, 100 consecutive navigated hip resurfacings were performed by a single surgeon (EHS). There were 80 males and 20 females in the cohort. The number of arthroplasties was divided evenly between left and right hips. The mean patient age was 51.9 years (SD 9.4 years, Range 26-82 years). Clinical diagnoses included primary osteoarthritis (OA) in 92 patients, OA second to developmental hip dysplasia in 2 patients, OA second to slipped capital femoral epiphysis in one patient and avascular necrosis in 5 patients.

3.5.3.1.2 Operative Procedure

Prior to the procedure, pre-operative templating was performed using digital AP unilateral hip radiographs (Figure 23). A standard radiography positioning protocol was utilized placing the patient in AP neutral position with no femoral rotation. The source to image distance was 100 cm centered over the proximal femur. The femoral shaft axis was drawn as a line from the most distal visible diaphyseal midpoint to a point approximating the piriformis fossa. Next a line was drawn through the isthmus of the neck toward the lateral cortex intersecting the femoral shaft axis. This was the neck axis and the angle subtended by the femoral neck and shaft axes was the neck-shaft angle (NSA). Component sizes were then chosen. The femoral component was positioned in an appropriate amount of relative valgus orientation. The angle the femoral component stem made
with the femoral shaft axis was the stem-shaft angle (SSA). A SSA that is approximately 5 to 10 degrees of relative valgus is routinely planned as has been recommended in the literature and shown to strengthen the proximal resurfaced femur (1;4;6;8;24;25). The values of the neck-shaft and stem-shaft angles were recorded for use during intra-operative navigation.

![Figure 23](image)

Figure 23. Pre-operative plan depicting femoral neck-shaft angle and planned stem-shaft angle and implant size

Patients were placed in the lateral decubitus position and a posterolateral approach was utilized. The femoral head was prepared according to standard surgical protocol with the use of imageless
computer navigation for placement of the initial guidewire. A Birmingham Hip Resurfacing (Smith & Nephew Inc., Memphis, TN, USA) was implanted in all cases.

3.5.3.1.3 Imageless Computer Navigation

Imageless computer navigation utilizes infrared camera technology to register anatomic landmark and surface data to create a patient specific proximal femoral model. The Vector Vision SR 1.0 imageless navigation system (BrainLAB, Heimstetten, Germany) was used to intra-operatively plan the position of and insert the initial femoral guidewire. The methodology for patient registration has been previously described (19). The navigation system acquires several anatomic landmarks for determination of the anatomical axes. The medial and lateral epicondylar points and the piriformis fossa delineate the diaphyseal axis. The superior head-neck junction is selected and the surfaces of the femoral head and neck are digitized. The femoral head diameter determines the computed implant size and the head-neck junction is used to initially situate the implant. The system uses point clusters acquired on the superior and inferior neck to determine the neck-shaft angle by fitting a plane to each cloud of points. A mid-plane between the two is calculated and the inclination of the mid-plane to the diaphyseal axis is the computed neck-shaft angle (26).

Upon registration, a patient specific morphed model is created. The system performs a notching check and adjusts the implant size until the notching condition is satisfied. The system calculates a neck-shaft angle as well as a recommended femoral component size. These computed values can be accepted or modified using the surgical planning screen prior to guidewire drilling (Figure 24). Once the surgical plan is satisfactory, a navigated hand-held drill guide is used to drill the initial guidewire. The remainder of the standard surgical protocol is followed for preparation of the femoral head.
3.5.3.2 Cadaveric Registration

To investigate the relative accuracy and reliability of the registration process, ten denuded adult left cadaveric femora were obtained (Pacific Research Laboratories, Vashon, WA, USA). Four fellowship trained orthopaedic surgeons, familiar with navigation, registered the 10 cadaveric femora 3 times each for a total of 30 registrations performed by each surgeon. Femurs were prepared with a static array fixed in the lesser trochanter and positioned in a maximally internally rotated and adducted position simulating the operative position of the femur (Figure 25). Surgeons were instructed to acquire anatomic landmarks according to the landmark positions indicated on the navigation screen and register anatomic areas by distributing points randomly throughout the areas indicated by the navigation prompts. Computed NSA and implant size were recorded for statistical analysis. Prior to registration, a digital anteroposterior radiograph of each femur was...
obtained. Femurs were positioned with the plane of the neck parallel to the radiograph cassette with a source to image distance of 100 cm centered over the neck. Radiographs were digitally measured for neck-shaft angle by the same observer who performed all pre-operative templating in the clinical series. Femurs were also assessed by the same observer for implant size using a neck gauge prior to registration. Surgeons were blinded to the NSA measurement and neck gauge results prior to performing the registrations. A second observer repeated the neck-shaft angle measurements for the 10 femurs to determine the reliability of neck-shaft angle measurement.

Figure 25. Cadaveric femur fixed with static array in lesser trochanter. Each femur was positioned in the bone vise and registered according to the navigation system requirements.
3.5.3.3  Statistical Analysis

For analysis of differences within and between surgeons, Excel and the statistical software package SPSS13 (SPSS Inc., Chicago, IL, USA) were used. One-way ANOVA with Tukey post hoc analysis was performed comparing the differences in computed NSA between surgeons. A Pearson Chi-Square analysis was used to compare categorical data for the computed implant size between surgeons for each femur. A p value of 0.05 was considered significant. An intraclass correlation coefficient (ICC) was computed to estimate the within and between surgeon reliability in computed NSA as well as the reliability between observers in neck-shaft angle measurement of the 10 cadaveric femurs. An ICC indicates the proportion of the total variance in measurement results that can be explained by differences between individuals. ICC values range from 0 to 1 with values greater than 0.75 considered acceptable (27). A two-way, absolute, random effects model measuring single measure reliability was used with the participating surgeons considered a random sample from a larger sample of surgeons. A generalized kappa statistic was used to determine the reliability in computed implant size between surgeons. A SPSS macro (28) was utilized to compute the level of agreement for categorical data between multiple observers. This measure is analogous to the ICC used for continuous data. The interpretation guideline established by Landis and Koch (29) was used in evaluating the strength of agreement using the generalized kappa statistic.

3.5.4  Results

3.5.4.1  Clinical Series

Pre-operative planning determined a mean NSA of 131.7 degrees (SD 4.5 degrees, Range 115-144 degrees). The navigation system computed a mean NSA of 137.5 degrees (SD 20.2 degrees, Range 90-180 degrees). The mean absolute difference between the pre-operatively planned and computed NSA was 16.3 degrees (SD 12.4 degrees, Range 0-52 degrees). The relative range of values for computed compared to measured NSA was 42 degrees of varus to 52 degrees of valgus (Figure 26).
In this series, 60 computed NSAs were valgus, 38 varus and 2 equal to the pre-operatively planned NSA. Of the 60 valgus computed NSAs, 42 were greater than 10 degrees. Only 16 of the computed NSAs were within an acceptable range of ± 3 degrees of the measured NSA. A varus computed NSA poses the danger of a varus aligned implant. Of the 38 varus computed NSAs, 21 were greater than 10 degrees. The 17 remaining computed NSAs were divided with 12 of less than 5 degrees of varus and seven between 5 and 10 degrees of relative varus. This latter group of relative varus computed NSAs poses the greatest pitfall for implant alignment planning.

Navigation tended to overestimate the component size. In 76 of the 100 cases, a larger component than the one implanted was recommended, while in 13 cases, the navigation software correctly
recommended the femoral component size to use. In the remaining 11 cases, the system recommended an implant size smaller than the one implanted. While an oversized implant may reduce the risk of femoro-acetabular impingement, it also leads to greater resection of acetabular bone stock. Conversely, an undersized implant may lead to notching of the neck during reaming preparation as well as an increased likelihood of impingement.

3.5.4.2 Cadaveric Registration

Measurement of the ten cadaveric femurs by digital radiographs yielded a NSA range of 116 to 132 degrees (mean 127.5, SD 4.6). The two observers showed good agreement measuring the neck-shaft angle of the cadaveric femora with a mean difference in measurement of 1.1 degrees (SD 2.3 degrees, ICC 0.853). Upon completion of the surgeon registrations, the mean absolute difference between the measured and computed NSA was 5.4 degrees (SD 4.4 degrees, Range 0-24 degrees). The relative difference of computed to measured NSA values ranged from 22 degrees of varus to 24 degrees of valgus. Figure 27 illustrates a box and whisker diagram of the computed NSAs for the 10 femurs. There were significant differences in computed NSA between surgeons for 3 of 10 cadaveric femora (p<0.041). The average difference in computed NSA between multiple registrations of a femur by a single surgeon was 5.5 degrees (SD 4.3 degrees, Range 0-29 degrees). The within surgeon intraclass correlation coefficient for computed NSA was acceptable in two cases (ICC>0.810) while poor in the remaining two (ICC<0.246). These values indicate that a high level of repeatability was obtained for two of the participating surgeons while the navigation process was far less repeatable for the remaining two surgeons. When comparing computed NSAs across all four surgeons, the between surgeon ICC was 0.131. This indicates a very low level of repeatability in computed NSA output between multiple users.
The navigation system tended to overestimate the implant size. Of the 120 registrations performed by the 4 surgeons, only 46 (38%) suggested the correct implant size identified by use of the neck gauge. The remainder of registrations oversized estimation of the implant size, with 6 oversizing the correct implant by two full sizes. There were significant differences between surgeons in the computed implant size in 2 of 10 femurs (p<0.029). The generalized kappa statistic was 0.155 indicating only a slight level of agreement in the computed implant size between surgeons.
3.5.5 Discussion

Computer assisted navigation shows potential for application in hip resurfacing arthroplasty. The current series demonstrates some of the difficulties and challenges new users to this technology may encounter. Sixty navigated hip resurfacings were conducted by the senior surgeon prior to this series, and while the current series does not include the initial learning curve, it does demonstrate the experiences of a surgeon proficient in the use of imageless navigation for hip resurfacing.

Several mechanical factors have been identified and demonstrated to predispose the resurfaced femur to premature failure including femoral neck notching and varus implant alignment (1-11;24;25;30-33). With the use of navigation, the aim is to minimize the occurrence of these preparatory errors. This series showed that the average discrepancy between the measured and computed NSA was 16 degrees. This is considerable in and of itself; however the absolute range of error was shown to be three times this value. While most surgeons would identify grossly inaccurate estimates of the NSA, it is the values that lie within a much smaller range of the true NSA that may lead users to plan erroneous implant angles. Specifically, the angles that lie between 5 and 10 degrees of varus to the true NSA may appear legitimate in the absence of an accurate pre-operative template. Correction for this initial relative varus NSA with a relative valgus SSA of 5 to 10 degrees may still yield a final coronal implant alignment that is varus to the native neck-shaft angle.

Selection of the correct femoral implant size is crucial to preservation of adequate bone stock and facilitation of proper bone resection. Navigation tended to overestimate the correct implant size in both the clinical and laboratory settings. While the navigation system did not undersize the implant in the laboratory setting, it did in the clinical setting which presents the risk of neck notching if the computed implant size is accepted and this likelihood is enhanced with relative valgus positioning of the implant. Component sizing should be conducted via a pre-operative plan and verified by neck gauge intra-operatively to ensure optimal implant selection. In the author’s experience, the computed implant size and NSA were often abandoned in favour of pre-operative NSA and implant size measurements. Implant size selection was further verified by neck gauge intra-operatively.
Within this paper, neither implant translation nor version have been addressed. While these are important factors in optimal component implantation, the current navigation software does not initially quantify these variables. The planning software first positions the component using the superior head-neck junction point as a marker for implant depth, then aligns it according to the neck axis delineated by the centre of the femoral head and the selected piriformis fossa point. Femoral head deformity is common in patients receiving a hip resurfacing with the femoral head often retroverted and deficient anterosuperiorly. Initial determination of the neck axis based on the femoral head center may lead the planning algorithm to suggest posterior translation and relative retroversion of the femoral component. As a result, it is the author’s routine practice to ensure that the planned implant position is correct relative to the acquired anterior and posterior femoral neck points thus adequately situating the implant both in translation and version.

Several investigators have examined the accuracy and precision of femoral implant translation and version using imageless navigation. Using dry bone models with optimal CT-based planning, Cobb et al. (15) compared imageless navigation to conventional instruments and CT-based navigation for placement of the initial femoral guidewire. All three methods showed similar levels of accuracy in anterior-posterior translation with CT-based navigation providing superior precision (SD 1.6 mm) compared to conventional jig (SD 3.4 mm, p<0.003) and imageless navigation (SD 6.2 mm, p<0.001). A similar finding was demonstrated for guidewire version with comparable accuracy among the three methods, however imageless navigation exhibited the poorest precision (SD 9 degrees) compared to CT-based navigation (SD 2 degrees, p<0.001) and conventional instrumentation (SD 5 degrees, p=0.015). In contrast to this finding, Resubal and Morgan (20) showed that imageless navigation (SD 1.53 degrees) was significantly more precise in femoral component version than mechanical jig (SD 4.36 degrees, p=0.025) while demonstrating no difference in accuracy between the two methods. In a prospective randomized study, Hart et al. (17) found that navigation provided both significantly greater accuracy and precision in anterior-posterior implant translation than did a conventional jig. Numerous studies have demonstrated the increased accuracy and precision of imageless navigation compared to conventional jigs in coronal implant alignment (16;17;20;22;23;34-36) with similar results to CT-based navigation (15), however, the contrasting literature with respect to implant version (15;17;20;35;36) indicates the inherent inconsistency in assessing this variable and warrants further investigation of the utility of imageless navigation in this regard.
The author identifies several limitations in the current study. Measurement error during pre-operative planning on AP hip radiographs may occur if the pre-operative films exhibit patient malposition or deformed and obscured patient anatomy. It has been shown that rotational errors of the femur may contribute to erroneous measurement by radiographs (37-40) and this can result in discrepancies between the pre-operatively planned data and that registered by the navigation system. The cadaveric arm of the study eliminated the effect of radiographic malposition and may partially explain the lesser range of error between the measured and computed NSA observed during cadaveric registration compared to that in the clinical series. In addition, while the cadaveric registration arm of the study did not exactly replicate the clinical setting for registration of the femur in hip resurfacing, it provided an optimal setting for evaluating the relative accuracy and reliability of the navigation process. Registration of denuded femurs presents a best-case-scenario in which complicating factors such as proximal femoral deformity, registration point visibility and soft tissue effects have been removed. There existed significant differences in computed NSA between surgeon registrations of the same femur in 3 of 10 femurs indicating that although a uniform registration technique was aimed for, the registration output appears sensitive to variations in the registration technique.

In conclusion, there is growing evidence supporting the use of imageless computer navigation for hip resurfacing arthroplasty (12;16;17;19-23;34-36). However, in order for navigation to truly be beneficial, the user must be aware of the limitations and challenges, in addition to the benefits, of this tool. Computer navigation cannot correct for poorly selected patients or improperly implanted components and thus it is imperative that the surgeon prudently select patients and conducts a thorough pre-operative template prior to performing navigated hip resurfacing. Strict reliance on data obtained during intra-operative navigation may yield erroneous implant selection and placement and thus a comprehensive pre-operative plan is vital to the success of the procedure utilizing imageless navigation.

3.5.6 References


26. Personal communication from BrainLAB.


CHAPTER 4
FEMORAL HEAD PREPARATION

4.1 Prologue

Hip resurfacing arthroplasty utilizes a bone preserving technique for preparation of the proximal femur in which much of the femoral neck and head are spared. Preservation of the femoral neck however, inherently poses the risk of femoral neck fracture. Neck fracture occurs in approximately 1-3% of patients and is the leading cause for revision in hip resurfacing. Several neck fracture risks have been speculated upon in the clinical literature including femoral neck notching, varus implant alignment and exposed, reamed cancellous bone. These fracture risks have mainly been identified by means of retrospective clinical reviews and there exists a lack of biomechanical investigation into these potential fracture precursors. This section investigates the mechanical basis for femoral neck fracture through the testing of synthetic and cadaveric resurfaced femora and looks to extrapolate results by means of finite element modeling. This chapter is comprised of three refereed journal articles recently published or accepted for publication (Davis et al. 2008, Davis et al. 2009, Olsen et al. 2008). The author thanks Dr. Edward Davis for contributions made to the methodology, experimental analysis and manuscript preparation within this chapter.

4.2 Femoral Neck Fracture following Hip Resurfacing: The Effect of Alignment of the Femoral Component

4.2.1 Abstract

A total of 20 pairs of fresh-frozen cadaver femurs were assigned to four alignment groups consisting of relative varus (10 and 20 degrees) and relative valgus (10 and 20 degrees), 75 composite femurs of two neck geometries were also used. In both the cadaver and the composite femurs, placing the component in 20 degrees of valgus resulted in a significant increase in load-to-failure. Placing the component in 10 degrees of valgus had no appreciable effect on
increasing the load to failure except in the composite femurs with varus native femoral necks. Specimens in 10 degrees of varus were significantly weaker than the neutrally-aligned specimens. The results suggest that retention of the intact proximal femoral strength occurs at an implant angulation of $\geq 142$ degrees. However, the benefit of extreme valgus alignment may be outweighed in clinical practice by the risk of superior femoral neck notching, which was avoided in this study.

4.2.2 Introduction

Excellent short- and medium-term results have been reported with the new generation of hip resurfacing arthroplasties (1-7). The advantages of preserving proximal femoral bone stock, the low dislocation risk and the excellent wear characteristics make resurfacing an attractive alternative to total hip replacement. However, concerns about the risk of femoral neck fracture and the consequences of metal ions still remain (8). Alignment of the femoral component has been associated with an increased risk of femoral neck fracture in retrospective reviews (9-13) and in finite element analysis (14,15). The purpose of this study was to establish the effect of orientation of the femoral component on the risk of fracture of the femoral neck.

4.2.3 Methods and Materials

The study was conducted in two phases. The first tested fresh-frozen cadaver femurs and the second used synthetic composite femurs with two different neck geometries.

4.2.3.1 Cadaver Specimen Testing

Twenty pairs of fresh-frozen cadaveric femurs were obtained. Each pair was the left and right femurs from the same donor. Local ethics committee approval was obtained. The median age of the donors was 71 years (53 to 90); 12 were male and eight were female. Femurs were defrosted for 24 hours prior to testing.
Pairs of femurs were assigned randomly to four alignment groups, namely relative varus (10 and 20 degrees) and relative valgus (10 and 20 degrees). Each pair contained one control specimen in neutral alignment and the other at the experimental alignment value. Neutral alignment was taken as when the stem-shaft angle (SSA) of the femoral component was at the same angle as the neck-shaft angle (NSA) of the femur. All specimens underwent pre-preparation scaled digital radiographs and bone mineral density measurements using a Dual Energy X-ray Absorptiometry (DEXA) scan (Hologic, Bedford, MA, USA).

The femurs were prepared using imageless computer navigation (VectorVision SR, BrainLAB, Feldkirchen, Germany) to position the initial guidewire during preparation of the femoral head. Specimens were individually registered and digitally mapped using an infrared camera and array system. Planning was performed using the VectorVision SR console for the position of the implant and the alignment angle. An infrared handheld drill guide, providing real-time location relative to the planned location and angle, was used to insert the guidewire. This wire was the basis for the remainder of the standard preparation of the femoral head, including central canal drilling, reaming and chamfering. Once prepared, the appropriate Birmingham Hip Resurfacing (BHR) component (Smith & Nephew Inc., Memphis, TN, USA) was cemented on to the prepared femoral head using polymethylmethacrylate (PMMA) bone cement (Stryker Howmedica Osteonics, Allendale, NJ, USA). Implant size was determined from the width of the femoral neck using the standard BHR measurement tool (Smith & Nephew Inc., Memphis, TN, USA). All implants were positioned in neutral version. The femoral neck was closely inspected to ensure that no notching had occurred. Implants were impacted in place and the stem-shaft angle was verified to confirm that no fracture had occurred, using scaled digital radiographs.

The prepared femurs were then sectioned 17 cm below the tip of the greater trochanter and potted using cement in 7 cm-high chambers. There was 10 cm of proximal femur left exposed. The potted femurs were placed in the position of single-leg stance and tested in axial loading to failure using an Instron mechanical testing machine (Model 8874, Instron, Canton, MA, USA).
4.2.3.2 Synthetic Specimen Testing

The use of Third Generation Composite Femurs (Pacific Research Laboratories Inc., Vashon, WA, USA) has been well validated as replicating the gross mechanical behaviour of cadaver bone (16,17). The availability of cadaver tissue often limits sample size. The reproducible properties of synthetic bone were thus used to examine the effect of alignment in further detail. Two composite femur models were examined, a medium left femur with a native neck-shaft angle of 135 degrees and a large left femur with a neck-shaft angle of 120 degrees (composite femur models 3303 and 3306, respectively; Pacific Research Laboratories Inc., Vashon, WA, USA). The 135 degree neck-shaft angle femurs were initially chosen to attempt to validate the synthetic model against cadaver results. The 120 degree model was then used to examine the effect of alignment of the femoral component in more detail in a model reproducing a varus native femoral neck.

A total of 30 femurs with a neck-shaft angle of 135 degrees were divided into six groups of five specimens each. One group was assigned to be the intact group tested without an implant, a second control group was tested with the implant in neutral alignment at the native neck-shaft angle of 135 degrees, and the remaining four groups were prepared in relative varus and valgus (10 and 20 degrees each). A total of 45 femurs with a neck-shaft angle of 120 degrees were divided into nine groups of five specimens each. One group was assigned to be an intact group tested without an implant, a second was assigned as a control group with the implant in neutral alignment at the native neck-shaft angle of 120 degrees. The remaining seven groups were prepared in relative varus (5, 10 and 15 degrees) and relative valgus (5, 10, 15 and 20 degrees). As in the specimen testing, all the femoral neck implants were positioned in neutral version and were closely inspected to ensure that no notching had occurred.

The synthetic femurs were prepared in the same way as the cadaver femurs, using imageless navigation to position the initial guidewire followed by standard preparation of the femoral head. The femurs were sized for the appropriate BHR component (42 mm for composite femur model 3303 and 46 mm for composite femur model 3306, Smith & Nephew Inc., Memphis, TN, USA), and cemented on to the prepared femoral head using PMMA bone cement. Implants were impacted in place and the stem-shaft angle was verified by scaled digital radiographs. All components were verified to be within ±2 degrees of the intended alignment angle.
Following resurfacing, each specimen was orientated in approximately 7 degrees of adduction in the coronal plane and aligned vertically in the sagittal plane to simulate anatomical loading in single-leg stance (18). Distally, both femoral condyles were secured with threaded pins and mounted in a stainless steel jig. Proximally, the femoral head was inserted into an obliquely sectioned stainless steel cup which was orientated with no ante- or retroversion with respect to the femoral neck. The femoral head was not fixed, but was free to rotate inside the cup. Specimens were loaded in axial compression using an Instron mechanical testing machine (Model 8874, Instron Corp., Canton, MA, USA). The tester was equipped with a load cell having ± 25 kN capacity, 0.1 N resolution, and ± 0.5% accuracy. The load-to-failure for each resurfaced femur was determined by applying a vertical force (displacement control, 10 mm/min, preload = 100 N) to generate axial compression until failure. Fracture patterns of the bone and implant at failure were recorded.

4.2.3.3 Statistical Analysis

The statistical software package SPSS13 (SPSS Inc., Chicago, IL, USA) was used to analyze differences between alignment groups in both the synthetic and cadaveric specimens. A paired t-test was used to compare bone mineral density, femoral geometry in cadaveric specimens and pre-and post-implant stiffness in synthetic femurs. One-way ANOVA with Tukey post hoc analysis was performed comparing failure loads between cadaveric specimen alignment groups as well as comparing the differences in post-implant stiffness and ultimate load-to-failure between the individual resurfaced alignment groups for both native neck-shaft angle synthetic femur geometries. A p-value of 0.05 was used to determine statistical significance.

4.2.4 Results

4.2.4.1 Cadaver Specimens

The paired specimens were well matched for bone mineral density (BMD) and proximal femoral geometry (Table 3). The load-to-failure results for the four different stem angles are shown in Figure 28. Placing the component in a relative valgus alignment of 20 degrees resulted in a significant increase in mean load-to-failure of 22% between experimental and control specimens.
There was no significant difference between the remaining alignment groups (p>0.29); however, a trend was observed with 10 degrees of varus alignment reducing the mean ultimate load-to-failure by 16% between experimental and control specimens (6008 N; SD 1304 vs. 7146; SD 2253, p=0.29). Placing the component in 10 degrees of valgus did not appear to have a significant effect on proximal femoral strength (p=0.836).

Figure 28. Graph showing the load to failure values for cadaver specimens

Table 3. Cadaveric Bone Mineral Density (BMD) and proximal femoral geometry

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>Experimental</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total proximal femoral BMD (g/cm²)</td>
<td>0.86 (0.78-0.94)</td>
<td>0.87 (0.79-0.96)</td>
<td>0.18</td>
</tr>
<tr>
<td>Femoral neck shaft angle (degrees)</td>
<td>126 (124.6-127.8)</td>
<td>126 (123.3-128.2)</td>
<td>0.65</td>
</tr>
<tr>
<td>Femoral Offset (mm)</td>
<td>44 (41.8-45.6)</td>
<td>43 (41.5-45.2)</td>
<td>0.56</td>
</tr>
<tr>
<td>Femoral Neck width (mm)</td>
<td>32 (30.8-33.8)</td>
<td>32 (30.9-33.9)</td>
<td>0.72</td>
</tr>
<tr>
<td>Femoral head diameter (mm)</td>
<td>47 (45.2-49.2)</td>
<td>48 (45.6-49.4)</td>
<td>0.14</td>
</tr>
</tbody>
</table>

95% CI, 95% Confidence Interval
4.2.4.2 Synthetic Specimens

The mean axial load-to-failure for the 135 degree neck-shaft angle intact specimen group was 6491.5 N (SD 441.8), which was not significantly different from the mean axial load-to-failure for the 120 degree intact group of 6855.8 N (SD 450.2, p=0.232).

The 135 degree intact specimens had a significantly greater mean load-to-failure than specimens prepared in 10 degrees of relative varus alignment (p=0.006), but were not significantly stronger than any other alignment group tested (p>0.062). Ultimate load-to-failure values can be seen in Figure 29, where specimens prepared in 20 degrees of relative valgus were significantly stronger than all other resurfaced groups (p<0.024). Placing the component in 10 degrees of relative varus significantly weakened the resurfaced femur compared with the neutrally aligned component (p=0.035), whereas placing the component in 10 degrees of valgus had no appreciable effect on increasing the load-to-failure compared with neutral alignment (p=0.999).

The 120 degree intact specimens had a significantly greater mean load-to-failure than neutral and varus aligned resurfaced specimens (p<0.005), but were not significantly stronger than specimens prepared in any degree of valgus orientation (p>0.207). Ultimate load-to-failure values can be seen in Figure 30, where specimens prepared in 20 degrees of relative valgus were significantly stronger than those prepared in neutral or any degree of varus alignment (p<0.002).
Figure 29. Graph showing the ultimate load-to-failure for synthetic femora with a 135 degree native neck-shaft angle

Figure 30. Graph showing the ultimate load to failure for synthetic femora with a 120 degrees native neck-shaft angle
Specimens prepared in 10 degrees of relative valgus were significantly stronger than specimens with a neutral component \((p=0.017)\), but those in 10 degrees or less of relative varus had no significant effect on reducing the load-to-failure compared with neutral alignment \((p>0.135)\).

The load-to-failure for both synthetic geometries was standardized against the load-to-failure values for the intact femur (Figure 31). Regression analysis demonstrated that the mechanical strength of the resurfaced specimens would approximate that of the unresurfaced, intact femur if a minimum femoral component angulation of 142 degrees was achieved with respect to the two neck geometries studied.

![Figure 31](image.png)

Figure 31. Graph showing the standardized load to failure of all synthetic specimens (% difference from unresurfaced specimens) against component angulation (NSA, neck-shaft angle)
Failure patterns were consistent within each alignment group and between the synthetic and cadaver specimens. Failure in the resurfaced specimens originated at the superior bone-implant interface and propagated toward the medial calcar, exiting proximal to the lesser trochanter. Fracture of the intact synthetic femoral neck started at the superolateral piriformis fossa and propagated vertically toward the inferior neck at the superior margin of the lesser trochanter.

4.2.5 Discussion

The optimal alignment of the femoral component during resurfacing arthroplasty has remained an area of controversy since the initial designs in the 1970’s. Freeman (19) believed that it should be aligned with the medial trabecular system within the femoral neck. He showed that this system lies at approximately 20 degrees to the vertical (19). This implies alignment of the component with a stem-shaft angle of 160 degrees. This extreme angulation is technically difficult to obtain in the majority of hips and increases the risk of notching of the femoral neck (20) and of there being exposed cancellous bone at the rim of the component (9) which may predispose to femoral neck fracture (9,12,13,21). This angulation may also lead to the absence of superior bone supporting the implant and to an increased risk of ‘internal notching’ of the medial calcar, both of which have also been speculated to weaken the proximal femur and predispose to fracture. Internal notching occurs in current hip resurfacing techniques which require a central drill to be used to prepare the femur for the stem of the component.

The inherent difficulty of placing the component at 160 degrees leads others to advocate placing it in a less extreme position, and an absolute stem-shaft angle of 140 degrees has been suggested as a compromise (9). Beaulé et al. (11) reviewed 94 hips in patients < 40-years of age that had undergone hip resurfacing and found that a stem-shaft angle \( \leq 130 \) degrees was associated with adverse radiological changes or early failure. This rate of adverse outcome was 6.1 times greater than in the group in which the stem-shaft angle was > 130 degrees. A basic mathematical model was also constructed to predict the biomechanical consequences of alterations in alignment of the femoral component. This demonstrated an almost linear relationship between total stress within the superior femoral neck and stem-shaft angulation, with an increased angle (valgus placement) reducing the stress. Beaulé et al. (11) therefore suggested a valgus orientation of the femoral component. They also demonstrated that an increasing valgus position of the femoral component
during resurfacing was negatively correlated with femoral offset, and that the two variables were closely interrelated. The author therefore accepts that the apparent increased strength of the valgus positioning within this study will in part relate to the reduced offset and resulting bending moment; however, this is also directly comparable to clinical practice. Others have used finite element analysis to observe the changes in bone stresses, concluding that a valgus placement will reduce bone stress in the superior neck and hence potentially reduce the risk of fracture of the femoral neck (14,15). A recent investigation into the effect of implant alignment on load transfer and strain distribution in the resurfaced femur showed that a component which is aligned in 10 degrees of valgus reduced the strain in the superior neck, whereas a varus aligned component had the opposite effect (22). Although the study showed that orientation of the component had an impact on load patterns in the proximal femur, the others were unable to show that coronal alignment had an influence on the risk of fracture.

The new generation of hip resurfacing has excellent early to mid-term results (2-4) but the risk of early femoral neck fracture remains a concern. The 2007 Australian Orthopaedic Association National Joint Replacement Registry data from 8945 hip resurfacings revealed that 47% of revision procedures were performed for femoral neck fracture (23). The overall rate of fracture has been found to be 1% to 3% (9,12,13,24,25). A retrospective review of 50 femoral neck fractures following resurfacing showed that more than 5 degrees of varus alignment was observed in 71% of cases that fractured (13). This early failure due to femoral neck fracture is of great concern and therefore this amount of alignment was used as the baseline in the current study. The author acknowledges, however, that femoral component alignment may also contribute to the medium- and long-term risk of fatigue failure as alluded to by Beaulé et al. (11).

The cadaver testing in this study appears to show that an increased resistance to femoral neck fracture is only achieved once a stem-shaft angle of 20 degrees of relative valgus is obtained. Interestingly, it did not show a significant difference in proximal femoral strength when placing the component in 10 degrees of relative valgus compared with placing it in a neutral alignment. These data would appear to contradict those of others, in which a slight valgus position was felt to protect against neck fracture (11). Although significance was not obtained, there did appear to be a trend toward reduced proximal femoral strength when the component was placed in 10 degrees of varus alignment compared with the neutrally-aligned controls.
For both synthetic femoral geometries, 20 degrees of relative valgus alignment appeared to have the most dramatic effect on increasing proximal femoral strength, agreeing with the results in the cadaver tests. For smaller increments of alignment, however, the two femoral geometries had contradictory results. It appeared that 10 degrees of relative valgus alignment significantly strengthened the varus neck resurfaced femurs (120 degree neck-shaft angle) but had little effect on the more valgus necks (135 degree neck-shaft angle). Conversely, 10 degrees of relative varus alignment significantly weakened the more valgus resurfaced femurs but had little effect on the varus femurs. Regression analysis of the synthetic femurs showed that an absolute implant alignment of 142 degrees preserved femoral strength, compared with the intact, unresurfaced specimens.

These results suggest that a minimum of 10 degrees 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 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 degrees, with respect to the two neck geometries studied. Positioning the component in 20 degrees 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 degrees is exceeded.

The difficulties of studying cadaver bone are well demonstrated in this study. Despite the use of 40 femurs, and verifying that BMD and proximal femoral geometry were not significantly different between controls and experimental specimens, there was still wide variability between paired femurs. Avoiding the difficulties inherent in cadaver testing by using Third Generation Composite Femurs has been well validated in previous studies (16,17). A graph showing the mean percentage difference in load-to-failure from a neutrally-aligned component in both the cadaver and the synthetic tests shows them to be well matched (Figure 32). The findings for the 135 degree neck-shaft angle synthetic specimens confirmed the trends observed with the cadaver specimens. The fracture patterns observed were similar in both cadaver and synthetic specimens. This pattern of fracture propagating from the superolateral edge of the femoral component down to just proximal to the lesser trochanter is consistent with fractures observed in biomechanical
testing of cadaver specimens following hip resurfacing conducted by Markolf and Amstutz (26) and Anglin et al. (27). Anglin et al. (27) studied the effect of valgus positioning of the femoral component with a neutral alignment control in ten pairs of cadaver femurs. Similar to Markolf and Amstutz (26) they created a superior femoral neck notch in all specimens to determine the potentially beneficial effect of valgus implant alignment in conjunction with a superior femoral neck notch. Their results were similar to the present study, with an increased load-to-failure in the valgus aligned group. They stratified the specimens into those with high and low BMD showing that femoral component alignment had a greater effect on those specimens with a higher BMD.

Figure 32. Graph showing the mean percentage difference in load-to-failure from a neutrally-aligned femoral component for the cadaver and synthetic specimens (synthetic specimens with 135 degree neck-shaft angle)
An unexpected finding of the current study was highlighted with the cadaver and both synthetic geometries and showed a slightly increased proximal femoral strength in large degrees of relative varus alignment. This surprising finding of an initial reduction in proximal femoral strength and then a relative increase as the varus angulation increased is difficult to explain. It may be due to the stem of the femoral component engaging on the relatively strong trabecular and subcortical bone in the superior aspect of the base of the femoral neck, thereby increasing the strength of the resurfacing construct. Further work is needed to provide a satisfactory explanation for this phenomenon.

The findings are limited to a basic biomechanical model of the proximal femur and may not precisely replicate the behaviour of bone in vivo. The author accepts that the findings only represent failure with respect to femoral neck fracture, rather than cyclical loosening of the component. The absence of muscle attachments around the hip in the mechanical testing construct and the use of only axial compression are a limitation. This may limit the generalization of these findings, and thus, further work is needed to evaluate the effect of different loading regimes and the effect of muscle forces. However, it has been reported that under normal gait loading the femur is primarily in a state of axial compression (28,29) with previous literature supporting biomechanical testing conducted under this assumption (30).

The results of cadaver and synthetic tests appear to support the belief that placing the component even in a small amount of varus relative to the native neck-shaft angle may be detrimental to proximal femoral strength. A minimum of 10 degrees of relative valgus alignment may be beneficial in preventing fracture in varus native femoral necks, whereas exceeding 142 degrees of absolute alignment may reproduce the intact femoral strength in resurfaced femurs that have valgus neck geometry, thereby reducing the risk of femoral neck fracture.

4.2.6 References


4.3 A Biomechanical and Finite Element Analysis of Femoral Neck Notching during Hip Resurfacing

4.3.1 Abstract

Hip resurfacing is an alternative to total hip arthroplasty in which the femoral head surface is replaced with a metallic shell, thus preserving most of the proximal femoral bone stock. Accidental notching of the femoral neck during the procedure may predispose it to fracture. Therefore the effect of neck notching on the strength of the proximal femur was examined. Six composite femurs were prepared without a superior femoral neck notch, six were prepared in an inferiorly translated position to create a 2 mm notch, and six were prepared with a 5 mm notch. Six intact synthetic femurs were also tested. The samples were loaded to failure axially. A finite element model of a composite femur with increasing superior notch depths computed maximum equivalent stress and strain distributions. Experimental results showed that resurfaced synthetic femurs were significantly weaker than intact femurs (mean failure 7034 N, p<0.001). The 2 mm notched group (mean failure 4034 N) was significantly weaker than the un-notched group (mean failure 5302 N, p=0.018). The 5 mm notched group (mean failure 2808 N) was also significantly weaker than both the un-notched and the 2 mm notched groups (p<0.001, p=0.023, respectively). The finite element model showed the maximum equivalent strain in the superior reamed cancellous bone increasing with corresponding notch size. Fracture patterns inferred from equivalent stress distributions were consistent with those obtained from mechanical testing. A superior notch of 2 mm weakened the proximal femur by 24%, and a 5 mm notch weakened it by 47%. The finite element analysis substantiates this showing increasing stress and strain distributions within the prepared femoral neck with increasing notch depth.

4.3.2 Introduction

The new generation of metal-on-metal hip resurfacing is becoming an increasingly popular alternative to total hip replacement in the younger and more active patient with end-stage hip arthritis. There are now excellent short- to medium-term results appearing within the literature (1;2). One of the concerns when offering patients hip resurfacing is the potential early
complication of femoral neck fracture. The overall rate of femoral neck fracture is approximately 1-3% (3-7). However, fracture rates as high as 22% have been reported (8). One of the potential risk factors for developing a post-operative fracture is thought to be notching of the femoral neck during femoral head preparation. In one large cohort of hip resurfacings performed by multiple surgeons, it was suggested that 47% of femoral neck fractures were the result of femoral neck notching (7).

To the author’s knowledge, there has been no specific published biomechanical evidence that femoral neck notching reduces the proximal femoral strength following the new generation of metal-on-metal hip resurfacing. Therefore, the aim of the current study was to examine the effect of femoral neck notching on the biomechanical strength of the proximal femur and to investigate the effect of neck notching using a finite element model.

4.3.3 Mechanical Testing of Composite Femurs

4.3.3.1 Investigation Design

Twenty-four, large, left, Third Generation Composite Femurs (Model 3306, Pacific Research Laboratories, Vashon, WA, USA), with native neck-shaft angles of 120 degrees, were randomized into four test groups of six samples each. A sample size of six was chosen in order to enable detection of a clinically significant difference in failure load of approximately 15% if it was present. The chosen sample size was equal to the one used by Heiner and Brown (9) investigating the structural properties of synthetic femora and twice as large as those employed in other similar studies investigating mechanical testing of synthetic femora (10;11). The first group, a resurfacing control group, was prepared with no notch in the superior aspect of the femoral neck. The second and third groups were prepared with a 2 mm and 5 mm notch in the superior cortex, respectively. The last group was not prepared with a hip resurfacing prosthesis and was tested intact. Femurs were tested in axial compression for stiffness both pre- and post-resurfacing and subsequently tested to failure once resurfaced. Loading in axial compression, which effectively produces both bending and axial compression in the bone, was chosen as it is the dominant loading pattern experienced in the femur during gait (12;13). The intact group was also tested for stiffness in axial compression and was tested to failure immediately after. All groups were compared for axial stiffness and ultimate load-to-failure.
4.3.3.2 Axial Stiffness Testing

Each intact synthetic femur was oriented in approximately 7 degrees of adduction in the coronal plane and aligned vertically in the sagittal plane to simulate anatomical loading in one-legged stance (14). Distally, both femoral condyles were secured with threaded pins and mounted in a stainless steel jig. Proximally, the femoral head was inserted into a cup cut from an obliquely sectioned stainless steel cylinder, which was oriented with no ante- or retroversion with respect to the femoral neck. Femurs were loaded in axial compression using an Instron 8874 mechanical testing machine (Instron, Canton, MA, USA) (Figure 33). The tester was equipped with a load cell having ± 25 kN capacity, 0.1 N resolution, and ± 0.5% accuracy. Vertical load was applied at the femoral head to a maximum of 2 mm of vertical displacement (displacement control, load rate = 10 mm/min, preload = 100 N), and load and deflection values were recorded. The slope in the linear region of the load-deflection curve was used to compute axial baseline stiffness.

4.3.3.3 Composite Femur Preparation

Imageless computer navigation (VectorVision SR 1.0, BrainLAB, Heimstetten, Germany) was used to position the initial guidewire during femoral head preparation. Femurs in the three resurfacing groups were individually registered and mapped using the infrared camera and array system. Intra-operative planning was conducted via the VectorVision SR console for implant position as well as varus/valgus and ante/retroversion implant angles. To create a notch in the superior neck, the implant position was planned in an inferiorly translated position. An infrared tracked hand-held drill guide, providing real-time drill location relative to the planned implant location and angles, was used to insert the initial guidewire. This guidewire was the basis for the remainder of the standard surgical protocol for preparation of the femoral head including central canal drilling, femoral head reaming, and chamfering. All implants were positioned in 5 degrees of relative valgus alignment compared to the native neck-shaft angle with no ante- or retroversion compared to the native neck axis. Following reaming of the femoral head, the notch depth at the superior aspect of the femoral neck was measured by Vernier caliper and verified to be within ±1 mm of the intended notch size for the two notch groups.
Once prepared, the appropriate Birmingham Hip Resurfacing prosthesis (BHR 46mm, Smith & Nephew Inc., Memphis, TN, USA) was cemented onto the prepared femoral head using PMMA bone cement (Stryker Howmedica Osteonics, Allendale, NJ, USA). Implants were impacted in place ensuring complete seating of the component and were visually inspected to ensure there were no fractures present after impaction of the prosthesis. Femurs were then verified for implant stem-shaft angle by digital radiographs (Figure 34). All implants were verified to be within ±2 degrees of the intended stem-shaft angle. No fractures were visible upon radiographic examination.
4.3.3.4 Axial Load-to-Failure Testing

Following resurfacing, each femur was again fixed distally in the position of single leg stance and loaded proximally in the stainless steel testing jig. Vertical load was applied at the femoral head to a maximum of 0.5 mm of vertical displacement (displacement control, load rate 10 mm/min, preload 100 N), and load and deflection values were again recorded. The slope in the linear region of the load-deflection curve was used to compute post-implant axial stiffness. The choice of 0.5 mm as a maximum displacement minimized the chances of prematurely overloading the post-implant specimens with a notch, before the axial load-to-failure testing portion of the study. The load-to-failure for each resurfaced femur construct as well as the intact group was determined by applying a vertical force (displacement control, load rate 10 mm/min, preload 100 N) to generate axial compression until catastrophic failure of the femur occurred. Catastrophic fracture patterns of the bone and implant were examined.

4.3.3.5 Statistical Analysis

To determine the statistical significance of the differences between groups, the statistical software SPSS13 (SPSS Inc., Chicago, IL, USA) was used. A paired samples t-test was used to
compare differences between the pre- and post-implant stiffnesses of individual femurs. A one-way ANOVA with Tukey post hoc analysis was performed comparing the differences in stiffness and ultimate load-to-failure between the intact and resurfaced groups. A p-value of 0.05 was used to determine significance.

4.3.4 Finite Element Analysis

4.3.4.1 CAD and Finite Element Modeling

A solid model of a Third Generation Composite Femur (Model 3306, Pacific Research Laboratories, Vashon, WA, USA) was retrieved from the Biomechanics European Laboratory Finite Element Mesh Repository (15). The published model is a CT-based solid model having differentiated volumes for the cortical and cancellous bones, which has been previously used and experimentally verified using mechanical tests (16). The model has also been used in a recent study investigating knee notching in total knee arthroplasty (17). The model was imported into a CAD package (Solidworks Corporation, Concord, MA, USA) for modification to reflect the simulated testing construct geometry. The intact model was modified to accept a 46 mm Birmingham Hip Resurfacing implant (Smith & Nephew Inc., Memphis, TN, USA) with a 0.5 mm non-interdigitating, uniform cement mantle between the cancellous bone and the implant. The cement mantle was modeled to taper out on the cylindrical portion of the femoral head due to the line-to-line design of the BHR. This reflects retrieval analyses conducted by Morlock et al. (18) who noted a high degree of variability in cement mantle with the majority of cement to polarize in the apical portion of the implant and the distal cylindrical portion of the prepared head to often be deficient of cement. The implant was positioned in 5 degrees of relative valgus alignment to the native neck-shaft angle of 120 degrees, with neutral ante-/retroversion. Recent finite element analyses have shown a relative valgus implant orientation to mimic more physiological loading patterns in the proximal femur decreasing bone strain in the superior femoral neck (19-21). An obliquely sectioned cylindrical jig with a recessed cup was mated to the implant with 7 degrees of adduction in the coronal plane and no ante- or retroversion compared to the native femoral neck (Figure 35). This modeling simulated the mechanical testing construct used for the composite femora testing arm of the study. Models of notch depth 1, 2, 3, and 5 mm in the superior aspect of the femoral neck were created in addition to a no-
notch model (Figure 36). Notches were modeled with a 0.2 mm root radius similar to that found on the cylindrical reaming tool. An intact model that was not modified for a hip resurfacing prosthesis was also mated to the proximal testing jig and positioned in the same single-leg stance position.

Figure 35. CAD model of composite femur and loading jig.
Models were imported into a finite element package (ANSYS Inc., Canonsburg, PA, USA) and meshed using SOLID187 elements which are 3-D, 10-Node, tetrahedral structural solid elements. In a study by Viceconti et al. (22), tetrahedral elements were shown to most accurately mesh human femurs with a number of studies employing this type of element (23;24). Models were mesh refined until a convergence criterion of 10% for stress and strain values within regions of interest was exceeded with node and element numbers ranging from 30,661 and 17,882 respectively for the intact model to 221,826 and 148,333 respectively for the 5 mm notch model. Notch models were refined in the contact surface area between the cancellous bone and the implant as well as the notch radius in the cortical and cancellous bone (Figure 37). Contact surfaces between the cortical bone, cancellous bone, cement mantle, implant, and test jig were all assumed rigidly bonded. The tapered metaphyseal implant stem was not cemented and was thus modeled as debonded through its entire length except for the most apical portion of the stem where it meets both cement mantle and the mouth of the cylindrical canal which was modeled as fully bonded. Although contact between the implant and the test jig are not actually rigidly bonded in the experimental situation, the author’s experience indicates that there is negligible
motion at that interface during static axial loading, making the assumption suitable for finite element analysis. The distal portion of the femur model to the level of the adductor tubercle was modeled as a fixed support, and an axial force of 8000 N was applied to the top surface of the loading jig. This force magnitude approximates the maximum force applied in the mechanical testing arm of the study (7923 N) and agrees with the maximum physiologic force reported by Bergmann et al. (14) following a total hip arthroplasty. Mean load-to-failure values were also substituted into the respective FE models once they were determined for each of the mechanical testing groups.

![Figure 37. 5 mm notched model illustrating cancellous bone mesh refinement in the superior notch area](image)

### 4.3.4.2 Material Properties

The elastic moduli used for the cortical and cancellous bone were 10 GPa and 206 MPa respectively. Both materials had a Poisson’s ratio of 0.29 and match the values used by Cheung et al. (16) in a study investigating intramedullary nailing of a synthetic femur. These values are based on data supplied by the manufacturers of the Third Generation Composite Femurs (Pacific
Research Laboratories, Vashon, WA, USA) used experimentally in this study. In the case of the cortical bone, the values are the average of tensile and compressive values. The elastic moduli used for the CoCr and PMMA were 200 GPA and 2 GPa, respectively. The Poisson’s ratios used were 0.30 and 0.19, respectively. Values for CoCr and PMMA match those used by Watanabe et al. (24) in which they looked at the stress distribution of a resurfaced composite femur. The values used for stainless steel were a 200 GPa elastic modulus and a Poisson’s ratio of 0.3 obtained through the ANSYS material library. The cortical and cancellous bone, cement mantle, implant, and loading jig were all modeled as homogeneous, linear, elastic and isotropic solids. Based on these material assumptions, the models used in the present study are ideal for comparative analyses rather than absolute output measures. Human femoral bone mechanical behavior, in comparison, can be 20-200 more variable from specimen-to-specimen with regard to four-point bending, axial loading, and torsional loading tests (25) and shows no appreciable difference for axial and torsion rigidity compared to the Third Generation Composite Femurs used in this study (11). Material properties for human femurs are highly variable and several studies have shown that the apparent elastic modulus can range from as high as 441 to 3230 MPa for cancellous bone (26;27) and 19.9 to 25.0 GPa for cortical bone (28;29).

4.3.4.3 Evaluation of Results

The von Mises equivalent stress and strain distributions were evaluated for the testing construct. The reamed cortical-cancellous bone interface was of interest, particularly in the area of the superior femoral neck notch. Both von Mises equivalent stress distribution (16;24) and equivalent strain distribution (23;24) analyses have been reported in the literature in similar studies of finite element analysis of hip resurfacing. Previous work suggests that strain-based analysis may be more suitable when studying trabecular bone failure (27). This work suggests that trabecular bone yield strain is uniform within an anatomic site and is believed to behave isotropically.
4.3.5 Results

4.3.5.1 Axial Stiffness for Mechanical Testing of Composite Femurs

A comparison was made between construct stiffness obtained from the slope of the linear portion of the force-deflection curve from the initial axial stiffness tests performed for the intact femurs (i.e. "non-destructive test stiffness") and the final axial load-to-failure tests (i.e. "destructive test stiffness"). A comparison was also made between the mean stiffness of each of the resurfaced testing groups. The mean axial stiffness for all intact synthetic femurs was 1543 N/mm (SD 152) and for all resurfaced femurs was 1568 N/mm (SD 250). No significant differences in pre- and post-implant stiffnesses were found between individual bone models (p>0.176). Similarly, there were no significant differences found between the post-implant stiffnesses of each of the resurfaced groups (p>0.319). Finally, the high average linearity coefficient ($R^2$) of the load-displacement curves used to compute stiffness for both the pre-implant ($R^2=0.989$), post-implant with no notch ($R^2=0.990$), and post-implant with a notch ($R^2=0.995$) conditions indicates that specimens remained within the linear elastic range, thereby incurring no permanent damage prior to subsequent axial load-to-failure tests.

4.3.5.2 Axial Load-to-Failure for Mechanical Testing of Composite Femurs

A significant difference (p<0.023) in failure load was observed in all mechanical groups tested (Figure 38). Introduction of a resurfacing implant significantly weakened the proximal femur when compared to the intact femur and the inclusion of a superior femoral neck notch further diminished the resistance to axial load of the proximal femur following a hip resurfacing.
Catastrophic failure patterns observed were consistent within each group of composite femurs. Failure in the notched resurfaced femurs originated at the superior bone-implant interface and propagated toward the medial calcar (Figure 39A). Fracture initiation in the no-notch resurfaced femurs appeared to originate in the anterior and posterior regions of the reamed cortical-cancellous interface propagating again toward the inferior base of the neck (Figure 39B). The difference between fracture patterns observed in the notch and no-notch models may be the result of the presence of a stress riser located in the superior neck in the notch models and the absence of this stress riser in the no-notch models. The author postulates the no-notch model may have experienced a Poisson effect in which compression of the neck occurred in the craniocaudal direction and expansion occurred anteroposteriorly, thereby increasing stress in the anterior and posterior aspects of the neck. Neck fracture for the intact femurs tended to differ from the resurfaced femurs as fractures initiated at the lateral base of the superior neck and propagated in a vertical fashion toward the inferior neck at the superior margin of the lesser trochanter (Figure 39C). Introduction of a hip resurfacing implant appeared to alter the fracture mechanics of the
femur by introducing a stress concentration proximally at the distal rim of the implant thereby initiating fracture closer to the joint center.

![Fracture patterns](image)

Figure 39. Mechanical testing fracture patterns: A) 5 mm notch femur; B) No-notch femur; C) Intact femur

### 4.3.5.3 Finite Element Analysis Results

The equivalent strain was seen to increase in the superior aspect of the reamed cancellous bone with increasing degree of superior neck notch. The predicted equivalent strain values appeared to increase exponentially with increasing notch size (Figure 40). A 1 mm notch increased the equivalent strain in the superior reamed cancellous bone 3-fold compared to the no-notch model, a 2 mm notch increased the strain 7-fold, and a 5 mm notch increased this value 50-fold. The notched models all exhibited maximum equivalent strain values in the superior aspect of the reamed cancellous interface in the area of the notch (Figure 41). Corresponding equivalent stress distributions in the cortical bone in the area of the superior notch were consistent with equivalent strain values and agreed with fracture patterns observed in the mechanical arm of testing. Figure 42A illustrates the cortical bone equivalent stress distribution in the 5 mm notch model corresponding to the maximum equivalent strain condition. The area of stress concentration occurred at the superior cortical-cancellous bone interface with stress unloading toward the base of the inferior neck. It should also be noted that areas of lower stress occurred in the superior, reamed cancellous bone directly adjacent the implant indicating a condition of stress shielding.
The no-notch model showed relatively low strain magnitude in the superior aspect of the reamed bone but did show slightly increased strain values compared to the 1 mm and 2 mm notch models on the anterior and posterior surfaces of the reamed cortical-cancellous interface. The corresponding equivalent stress distribution agreed with the fracture pattern observed for the no-notch synthetic femurs in the mechanical testing arm of the study (Figure 42B). The intact model indicated increased levels of cortical bone stress occurring at the superior aspect of the lateral base of the neck as well as the medial calcar (Figure 42C). This finding is comparable to the fracture pattern observed with the intact synthetic femurs in which the fracture originated at the superolateral base of the neck exiting the inferior neck proximal to the lesser trochanter.

![Figure 40. Equivalent strain distribution according to notch size for maximum axial load condition and mean failure load condition determined from mechanical testing](image)

Following the mechanical testing of the two notch groups and the no-notch group, the mean ultimate load-to-failure for each group was substituted back into each respective FE model to
verify stress and strain distributions in the superior, reamed cortical-cancellous bone. The predicted equivalent strain was seen to increase with increasing notch size in a similar exponential fashion as the previous model predicted (Figure 40). A 2 mm notch increased the equivalent strain in the superior reamed cancellous bone 4.5-fold compared to the no-notch model, while a 5 mm notch increased this value 22-fold. Again, a relatively low strain magnitude was observed in the superior reamed cancellous bone of the no-notch model with levels of strain increasing on the anterior and posterior aspects of the reamed cancellous bone similar to the location of fracture in the mechanical testing arm. Corresponding equivalent stress distributions were consistent with the fracture patterns observed in the mechanical arm of testing.

Figure 41. Cancellous bone strain distribution for the 5 mm notch model
Figure 42. Equivalent stress distribution: A) 5 mm notch model; B) No-notch model; C) Intact model

4.3.6 Discussion

4.3.6.1 Clinical Implications of the Current Results

This study provides biomechanical and finite element evidence that the formation of a superior notch during femoral head preparation weakens the proximal femur, potentially predisposing it to femoral neck fracture. In the basic biomechanical testing, a notch of 2 mm weakened the proximal femur by 24% and a 5 mm notch weakened it by 47%, when compared to the bone model prepared with no notch in the superior cortex of the neck. The study also confirms that performing a femoral head resurfacing significantly weakens the proximal femur when compared to testing the intact femur, even when no notch is present.

These data support the clinical findings of an apparent increased risk of femoral neck fracture after hip resurfacing. Retrospective reviews of patients sustaining femoral neck fracture following hip resurfacing have suggested that femoral neck fracture may be associated with femoral neck notching, varus alignment of the femoral component, failure to cover exposed cancellous bone with the femoral component and cysts within the femoral head and neck (3;4;7;30-35). However, the retrospective nature of these studies makes it difficult to isolate confounding factors, particularly with respect to neck notching where abnormal anatomy and technical difficulties may lead to notching. There is still some considerable debate as to the exact mechanism leading to femoral neck fracture with some authors suggesting that it may be
due to vascular insufficiency rather than simply biomechanical factors. It has been suggested that superior neck notching may have a more detrimental effect on femoral head blood flow leading to femoral neck fracture, rather than simply causing a biomechanical weakening (36).

Furthermore, it must be noted that the synthetic femurs used presently were not specifically designed for femoral neck fracture testing. The cortex at the neck region of the synthetic femurs (2.5 to 3.0 mm) used is thicker than that measured in real human femurs (1.0 to 1.9 mm) (37). It may be, therefore, that human femurs in a clinical scenario will withstand even lower load-to-failure levels than currently obtained for synthetic femurs. However, catastrophic failure loads of the intact synthetic femurs used in the current study fall within the ranges reported in the literature for mechanical testing of human cadaveric femora (18;38-41).

4.3.6.2 The Previous Generation of Hip Resurfacing Devices

Studies from the previous generation of metal-on-polyethylene hip resurfacing and femoral fracture were limited. Markolf and Amstutz conducted a test of human cadaveric femurs following hip resurfacing (42). Ten fresh-frozen unilateral femurs were prepared with a femoral resurfacing component positioned in neutral alignment with no notch. The mean load-to-failure for the specimens was 8592 N (1929 lb). This exceeds the load-to-failure for the no-notch group of synthetic specimens in the current study (5302 N) possibly owing to a greater variation in cadaveric specimens tested. They noted fracture patterns of the cadaveric femora to be almost identical to those in the current study with the fractures propagating from the superior rim of the femoral component extending down to the superior margin of the lesser trochanter. In their group of tests, they also attempted to assess the effect of neck notching. In two pairs of cadaveric femurs they placed the femoral component in 20 degrees of valgus and created a superior neck notch. The control specimens were placed in neutral alignment with no neck notching. The femurs were then tested to failure. The results revealed that the femurs placed in a valgus alignment with notching of the femoral neck were 6% and 36% weaker than the control specimens. However, the small number of specimens and the wide variability in testing cadaveric specimens, even when pairs were used, was a significant weakness of this study (43). The addition of a valgus placement in the notched groups also provided another confounding variable as alignment has also been suggested to affect proximal femoral strength (3;7;30-34).
However, the suggestion that neck notching weakens the proximal femur in this previous generation of hip resurfacing would appear to be substantiated by the present study of the newer generations of hip resurfacing.

4.3.6.3 Current Mechanical Investigations of Femoral Neck Fracture in Hip Resurfacing

There continues to be minimal biomechanical investigation into the effect of preparation variables in hip resurfacing. In a recent study by Anglin et al. (44), the effect of implant alignment and neck notching were investigated utilizing 10 pairs of fresh-frozen cadaveric femora. Femur pairs were prepared with a control specimen in neutral implant alignment and an experimental specimen prepared in 10 degrees of relative valgus. Both femurs were prepared with a 2 mm superior neck notch. They found that valgus implant orientation strengthened the notched femur compared to the control femur in neutral alignment. Load-to-failure of the neutral control femurs of normal BMD with a 2 mm notch in the investigation by Anglin et al. (44) occurred at approximately 4100 N. This figure accords with failure loads of the 2 mm notch group in the current investigation of 4034 N lending support to the use of synthetic femurs in the present study.

4.3.6.4 Finite Element Analysis Implications

The use of finite element analysis in the study of hip resurfacing has previously been described in both the newer and older generations of hip resurfacing (23;24;45-48). However, to the author’s knowledge, the use of this technique to study the effect of femoral neck notching has not been undertaken. The FEA studies that have been conducted do appear to support the current finding that the act of placing a hip resurfacing component on the proximal femur does weaken the femur, even if neck notching is avoided (23;24;47). These studies have demonstrated using 2D and 3D models 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. The stress riser 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 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. The analysis of femoral neck notching in a CT-based synthetic model presented in the current study is limited, and further work is required to evaluate the effect of notching elsewhere on the femoral neck as well as extending the work to include modeling of notching in human femur models of varying material properties and geometries.

4.3.6.5 Experimental Limitations

There exist limitations to the experimental findings in this study. Firstly, a basic biomechanical model of the proximal femur using composite femurs may not precisely replicate the behavior of human bone in vivo. Although the use of Third Generation Composite Femurs has been well validated as replicating the gross mechanical behavior of cadaveric bone with respect to axial and torsional rigidity (11), no study has yet conclusively demonstrated that the same can be claimed for the weight-bearing trabecular area. Even so, a major advantage of using these bone analogues is that the difficulties associated with the large variability when working with cadaveric specimens are avoided, including large variation in cadaveric femora geometry, size, and bone mineral density (9;25). However, the use of uniform synthetic bone models also limits the generalizability of these findings. The synthetic bone models tested exhibited a relatively varus neck-shaft angle of 120 degrees. A relative varus NSA may be more susceptible to neck fracture than a femoral neck that has a more valgus orientation as a result of the increased femoral head offset and resultant bending moment present and thus a “worst case” for examining the effect of femoral neck notching may have been employed in the current study. The use of more valgus femoral necks may have the potential of reducing the detrimental effects of a superior neck notch. Secondly, the absence of hip joint muscle attachments in the mechanical testing construct and FE modeling are a limitation. The present study might model more tensile stress in the neck than actually occurs in vivo. The human femur is normally loaded by muscle forces which place the neck in compression, since it has been reported that under normal gait loading the femur is primarily in a state of axial compression (12;13) with previous literature
supporting biomechanical testing conducted under this assumption (16). Thirdly, the use of static loading in single-leg stance also limits the generalization of these findings. The position of axial loading in the coronal plane was chosen as the position more prone to failure. Previous work has demonstrated that the proximal femur is on average twice as strong when torque is applied in the sagittal plane when compared to the coronal plane (43). Concerns have also been expressed on the interpretation of data when cyclical testing is used when compared to static testing (42). Fourthly, the “large deformation effect” was not considered in the current investigation. However, the linear case was considered and is consistent with similar FE studies investigating the effect of a hip resurfacing prosthesis on the strain patterns in the proximal femur (20;21;23). A linear analysis was chosen as this was felt to be adequate to perform a comparative analysis of the effect of incremental notching of the superior cortex of the femoral neck. Lastly, despite visual and radiographic inspection of the prepared resurfaced femurs, it is possible that the femoral neck may have been weakened during the impaction process contributing to the weakening of the construct. Femoral component impaction has been speculated to introduce microfractures within the bone supporting the implant inherently weakening the resurfacing construct. This phenomenon is difficult to detect, however, as previous studies have detected the presence of microfractures by histological analysis (18).

4.3.7 Conclusion

The new generation of hip resurfacing is gaining increasing acceptance as a treatment option for young, active patients with hip arthritis. The concerns over femoral neck fracture are substantiated by the weakening of the proximal femur following hip resurfacing. The addition of a superior femoral neck notch during femoral head preparation appears to significantly weaken the proximal femur potentially leading to an increased risk of post-operative femoral neck fracture.

4.3.8 References


4.4 The Biomechanical Consequence of Exposed Cancellous Bone in Hip Resurfacing Arthroplasty

4.4.1 Abstract

Failure to completely cover reamed cancellous bone during femoral component impaction has been speculated to predispose to femoral neck fracture. The current study examined the effect of exposed cancellous bone on the strength of the resurfaced proximal femur. Composite femurs were prepared in three configurations: (1) Partial, with the implant placed at the native femoral head offset of the femur, partially exposing reamed cancellous bone along the perimeter of the prosthesis rim; (2) Proud, with a circumferential ring of exposed cancellous bone; and (3) Complete, covering all reamed cancellous bone. Specimens were loaded to failure in axial compression. A finite element model was used to further explore the effect of exposed cancellous bone, cement mantle thickness and relative valgus orientation on the strain distributions in the resurfaced femur. The Proud group (2063 N) was significantly weaker than both the Partial (2974 N, p=0.004) and Complete groups (5899 N, p=0.001) when tested to failure. The Partial group was also significantly weaker than the Complete group when tested to failure (p=0.001). All fractures were consistent within groups, initiating at the superior aspect of the neck, at the component-bone interface. The finite element model demonstrated increasing levels of strain in the superior reamed cortical-cancellous bone interface with increasing degree of exposed cancellous bone. The condition of the femoral component seated proud as the result of a thick cement mantle had the greatest detrimental impact on strain level in the superior reamed cancellous bone while a valgus oriented implant provided a protective effect. This study provides biomechanical evidence that exposed reamed cancellous bone significantly reduces the load-to-failure and increases maximum strains in the resurfaced proximal femur. The perceived benefit of reconstructing the femur to its native geometry may inherently weaken the proximal femur and increase femoral neck fracture risk if reamed cancellous bone remains exposed following implant impaction. Relative valgus orientation of the implant may help to minimize the risk of neck fracture if reamed cancellous bone remains exposed.
4.4.2 Introduction

Hip resurfacing is emerging as a viable option to total hip replacement in the younger, more active patient with end-stage osteoarthritis. Evidence supporting the strong short- to medium-term results is appearing in the literature (1-8). Despite the relative success of the latest generation of hip resurfacing, the risk of early femoral neck fracture remains a concern when offering patients this alternative. The overall rate of femoral neck fracture is approximately 1-3% (7;9-14) and is currently the most common indication for revision arthroplasty following hip resurfacing (15). Several potential risk factors have been identified in the literature that may predispose the prepared femur to post-operative neck fracture including neck notching, implant alignment, and exposed cancellous bone following impaction of the femoral component (3;6;9;10;13;14;16;17). Exposed cancellous bone can result from suboptimal femoral head preparation in which head planing does not extend sufficiently distal or from an excessive cement mantle underlying the proximal pole of the implant.

To the author’s knowledge there has been no specific published biomechanical evidence that exposed cancellous bone weakens the proximal femur following hip resurfacing. Thus, the aim of the current study was to investigate the effect of exposed cancellous bone on the biomechanical strength of the resurfaced femur and to investigate the effect of component depth using a finite element model.

4.4.3 Methods and Materials

4.4.3.1 Mechanical Analysis

The femoral head offset of a synthetic Third Generation Composite Femur (model 3306, Pacific Research Laboratories Inc., Vashon, WA, USA) was measured by digital AP radiograph using digital templating software (EndoMap v2.01, Hectec GmbH, Germany). The femur was positioned such that the plane of the neck was parallel to the radiograph cassette. A line was drawn along the midline of the diaphysis approximating the femoral shaft axis. A concentric circle was drawn approximating the diameter of the femoral head to determine the joint center. The perpendicular line drawn between the joint center and the femoral shaft axis was the femoral head offset (18-20) (Figure 43).
Eighteen Third Generation Composite Femurs were used in the study. Synthetic femur analogues have been well validated as replicating the mechanical properties of cadaveric bone without the difficulties associated with the large variability when working with cadaveric specimens (21;22). Specimens were divided into three groups of six specimens each. Prior to femoral head preparation, each intact specimen was tested for stiffness. Distally, the femur was mounted in a stainless steel jig and the femoral condyles secured with threaded pins. Proximally,
the femoral head was inserted into a cup cut from an obliquely sectioned stainless steel cylinder, meant to simulate the acetabular contact surface. Specimens were loaded in axial compression using an Instron 8874 mechanical testing machine (Instron, Canton, MA, USA) (Figure 44). The tester was equipped with a load cell having ± 25 kN capacity, 0.1 N resolution, and ± 0.5% accuracy. A 100 N pre-load was applied to the resurfaced femur to eliminate initial slipping of the contact between the jig and implant. Loading in axial compression was chosen as it is the dominant loading pattern experienced in the femur during gait (23;24). This load pattern effectively produces both bending and axial compression in the proximal femur. Vertical load was applied at the femoral head to a maximum of 2 mm of vertical displacement (displacement control, load rate 10 mm/min) and load and deflection values were recorded. The slope of the load-deflection curve was used to determine baseline stiffness of the intact composite femur.

Figure 44. Resurfaced specimen positioned in mechanical tester
The first group (Partial) was prepared with the implant placed at the native femoral head offset of the intact femur. This implant position covered reamed cancellous bone superiorly, however it left partially exposed cancellous bone elsewhere along the distal rim of the prosthesis (Figure 45). The second group (Proud) was prepared with the implant seated 5 mm proximal to the Partial group creating a ring of exposed cancellous bone with approximately 5 mm of exposed reamed cancellous bone superiorly. The third group (Complete) was seated 5 mm distal to the Partial group thus covering all reamed cancellous bone. Femoral head offset for the intact specimen as well as implant offset (equivalent of femoral head offset for the resurfaced femur) for the three resurfaced groups were compared statistically.

Femurs were prepared according to the standard surgical protocol. Imageless computer navigation was used for placement of the initial guidewire (VectorVision SR 1.0, BrainLAB, Heimstetten, Germany). The imageless navigation technique utilizes an infrared camera and array system to digitally register the proximal femur. A patient specific morphed model is generated and used to plan the position of the implant on the femoral head and neck and this information is then used to guide placement of the guidewire. All implants were planned in neutral coronal and transverse alignment in the femoral neck.

Following femoral head preparation, a 46 mm Birmingham Hip Resurfacing prosthesis (BHR, Smith & Nephew Inc., Memphis, TN, USA) was cemented onto the prepared femur using
PMMA bone cement (Stryker Howmedica Osteonics, Allendale, NJ, USA). Implants were impacted in place and verified for implant stem-shaft angle by digital radiographs. Femurs were positioned such that the plane of the femoral neck was oriented parallel to the film cassette. All implants were verified to be neutral to the native neck-shaft angle of the composite femur. The implant offset was also measured for each resurfaced femur using the same radiographs (Figure 43). Each resurfaced specimen was again fixed distally in the position of single-leg stance and tested using the Instron mechanical tester. Axial load was applied at the femoral head to a maximum of 0.5 mm of vertical displacement, minimizing the chance of premature fracture, and load and deflection values were recorded. The slope of the load-deflection curve was used to compute post-implant axial stiffness. Each resurfaced femur was then loaded to failure by applying an axial load until catastrophic failure of the femur occurred (displacement control, load rate=10 mm/min). Groups were compared for axial stiffness both pre- and post-resurfacing and ultimate peak load-to-failure once resurfaced. Catastrophic fracture patterns of the resurfaced femur were also examined.

4.4.3.2 Statistical Analysis

For analysis of the differences between groups, Excel and the statistical software package SPSS were used (SPSS Inc., Chicago, IL, USA). One-way ANOVA with Tukey post hoc analysis was performed comparing the differences in femoral head and implant offset, and both pre- and post-implant stiffness and ultimate load-to-failure between the three component depth groups. A p-value of 0.05 was used to determine significance.

4.4.3.3 Finite Element Analysis

A Third Generation Composite Femur model (Model 3306, Pacific Research Laboratories Inc., Vashon, WA, USA) was retrieved from the Biomechanics European Laboratory Finite Element Mesh Repository (25). Cheung et al. previously validated the model (26) and it has subsequently been utilized in a study investigating femoral cortex notching in total knee arthroplasty (27). The model has also been used by the authors to investigate femoral neck notching in hip resurfacing (28).
The intact model was adapted for a 46 mm Birmingham Hip Resurfacing implant with a 1.5 mm non-interdigitating cement mantle between the cancellous bone and the implant. The implant was positioned in neutral coronal and transverse alignment in the femoral neck. Models simulating the three component depth groups were created. An additional model was created at the same implant offset as the Proud group but with 5 mm cement mantle (Proud-Thick Mantle). Retrieval analysis by Morlock et al. (29) deemed cement mantles greater than 5 mm to be excessive and this cement mantle thickness was used by Radcliffe and Taylor (30) in a finite element study evaluating the impact of cement mantle thickness on strain distribution in the proximal femur. A fifth model was created with the implant positioned in 10 degrees of relative valgus alignment at the native femoral head offset of the intact femur (Partial-10 Valgus). Relative valgus placement of the femoral component has been suggested in order to avoid a varus implant orientation which has been speculated to predispose the femoral neck to fracture (6;9;13;16).

Models were meshed using SOLID187 elements which are 3-D, 10-Node, tetrahedral structural solid elements (ANSYS Inc., Canonsburg, PA, USA) (Figure 46). Tetrahedral elements were chosen, as opposed to hexagonal or mapped meshing, as they have been shown to most accurately mesh human long bones (31). Mesh density in the area of the reamed cancellous bone was iteratively increased until a convergence criterion of 10% for equivalent strain was achieved. Resulting mesh densities ranged from 102770 to 169006 nodes and 63629 to 108863 elements. All contact surfaces in the femur model were assumed rigidly bonded and the distal portion of the femur to the level of the adductor tubercle was modeled as a fixed support. The tapered metaphyseal implant stem was not cemented and was thus modeled as debonded through its entire length within the cylindrical stem channel. The load jig was constrained to the resurfacing implant with a no-separation boundary condition translating only in the z-direction. An axial force of 3500 N was applied to the top surface of the loading jig, so chosen as this force magnitude approximates the mean of the mechanical testing load-to-failure values. This load is comparable to those used in similar finite element studies investigating hip resurfacing (32;33) and agrees with the physiologic force reported by Bergmann et al. (34) for an active individual during fast walking or jogging following a total hip arthroplasty. Following the mechanical testing of the three implant position groups, mean ultimate load-to-failure values for each group
were substituted back into each respective FE model to verify strain distributions in the reamed cancellous bone.

The elastic moduli and Poisson’s ratios used for the cortical (10 GPa, 0.29) and cancellous (206 MPa, 0.29) bone match those used by Cheung et al. (26). These values are based on the values supplied by Pacific Research Laboratories, and in the case of the cortical bone, are the average of tensile and compressive values supplied for the Third Generation Composite Femur. Values for CoCr (200 GPa, 0.3) and PMMA (2 GPa, 0.19) match those used in similar finite element analyses investigating hip resurfacing (32;33;35;36). The values used for the stainless steel loading jig (200 GPa, 0.3) were obtained through the ANSYS material library. The cortical and cancellous bone, cement mantle, implant, and loading jig were all modeled as linear, elastic and isotropic solids which are common material approximations amongst FE studies (26;27;32;33;37).

Figure 46. Finite Element Model of resurfaced femur under mechanical loading condition
Both stress and strain based analyses of human long bones have been reported in the literature (26;27;32;33;35;36;38). Previous work suggests that strain-based analysis may better describe the failure mechanism of trabecular bone. This work suggests that trabecular bone yield strain is uniform within an anatomic site, being weakly correlated to apparent density (39), and is believed to behave isotropically (40). Equivalent strain distributions were evaluated in the proximal femur and specifically within the region of the reamed cancellous bone of the femoral head. Values were normalized against peak equivalent strain in the superior head-neck region of the complete model.

4.4.4 Results

4.4.4.1 Mechanical Analysis

Measurement of femoral head offset of the intact specimens by radiograph yielded a mean of 48.3 mm (SD 1.0 mm). In comparison, the mean femoral implant offsets of the Partial, Proud and Complete groups were 47.0 mm (SD 1.3 mm), 52.0 mm (SD 1.5 mm) and 43.2 mm (SD 0.9 mm), respectively. The implant offsets of the three resurfaced groups were significantly different from one another (p<0.001). However, the implant offset of the Partial group was not significantly different from that of the intact femur (p=0.279), essentially recreating the native anatomy.

Prior to resurfacing the femurs, the mean axial stiffness of all 18 intact specimens was 1534.0 N/m (SD 117.0 N/m). With a resurfacing implant in place, the mean axial stiffnesses of the Partial, Proud and Complete groups were 1475.8 N/m (SD 81.4 N/m), 1193.5 N/m (SD 70.5 N/m) and 1834.5 N/m (SD 108.6 N/m), respectively. The stiffnesses of the resurfaced femur groups were all significantly different from one another (p<0.001). The stiffness of the Partial group was not significantly different from that of the intact femurs (p=0.637). The high average linearity coefficient ($R^2$) of the force-displacement curves used to compute stiffness for both the intact ($R^2=0.990$), Partial ($R^2=0.995$), Proud ($R^2=0.996$) and Complete ($R^2=0.997$) groups indicates that specimens remained within the linear elastic range, thereby avoiding permanent damage prior to subsequent load-to-failure testing.
Catastrophic failure testing demonstrated a mean load-to-failure of 2063.3 N (SD 289.5 N) in the Proud group and this was significantly weaker than both the Partial (mean 2974.1 N, SD 412.0 N, p=0.004) and Complete groups (mean 5899.0 N, SD 479.7 N, p=0.001) when tested to failure (Figure 47). The Partial group was also significantly weaker than the Complete group when tested to failure (p=0.001).

Catastrophic failure patterns observed were consistent within each group of composite femur specimens. Failure in the Partial and Proud resurfaced groups originated at the superior cortical-cancellous bone interface and propagated toward the medial calcar in an oblique fashion (Figure 48). Fracture initiation in the Complete group of specimens appeared to originate in the superior femoral neck adjacent to the distal rim of the prosthesis propagating toward the inferior base of the neck in a slightly more vertical manner.

![Figure 47. Ultimate load-to-failure of resurfaced specimens. Both the Partial and Proud groups were significantly weaker than the Complete specimens (p<0.001)](image)
4.4.4.2 Finite Element Analysis

Overall, peak equivalent strain in the reamed cancellous bone of the femoral head increased with increasing degree of exposed cancellous bone (Figure 49). For the uniform load of 3500 N, peak equivalent strain doubled between the Partial and Proud implant positions. By fully seating the implant and covering all reamed cancellous bone, the peak strain decreased 5-fold compared to the Partial implant position. Placing the implant in 10 degrees of valgus resulted in a similar reduction in superior neck strain, however, strain in the inferior reamed cancellous bone increased by 57%.

A proud implant position, resulting from a thick cement mantle, appeared to have the largest impact on strain in the reamed cancellous bone with an increase of 15% compared to the equivalent offset Proud model and 140% compared to the Partial model. This effect is most markedly demonstrated when compared to the model with a fully seated implant in which the strain levels were increased nearly 15-fold. Similar strain patterns were observed when the mean load-to-failure values were substituted back into the respective finite element models. Areas of peak equivalent strain coincide with fracture patterns observed in the mechanical testing arm of investigation. Areas of peak strain in the Partial and Proud models occurred in the exposed cancellous bone areas of the superior prepared femoral head while those in the Complete model occurred in the superior femoral neck adjacent the distal rim of the implant (Figure 50).
Figure 49. Normalized equivalent strain in superior reamed cancellous bone region for finite element models at applied loads of 3500 N and mean load-to-failure values obtained from mechanical testing.

Figure 50. Finite element model demonstrating strain pattern in Complete model with 3500 N applied load. Strain was highest in the superior femoral neck adjacent the distal rim of the prosthesis.
4.4.5 Discussion

This study provides biomechanical evidence that exposure of reamed cancellous bone following impaction of the femoral component may weaken the proximal femur, potentially predisposing it to femoral neck fracture. Basic biomechanical testing demonstrated that placement of the prosthesis in a proud position, exposing a circumferential ring of reamed cancellous bone, weakened the resurfaced femur by 31% compared to the Partial group in which components were placed at the native femoral head offset. The presence of a circumferential ring of exposed cancellous bone has been previously identified as a prominent mechanical risk factor leading to fracture of the femoral neck in a recent clinical series (9). Slightly lateralizing the implant to completely cover all reamed cancellous bone dramatically strengthened the resurfaced femur increasing the failure load to twice that of the Partial group. Failure load values of the Complete group are comparable to similar studies looking at mechanical risk factors in hip resurfacing in both synthetic and cadaveric femurs (28;41), but are less than those of an earlier study investigating the previous generation of hip resurfacing in cadaveric femora (42). Hip resurfacing boasts the ability to reconstruct the patient’s native anatomy, however the current study demonstrated that in doing so, the resurfaced femur may be inherently weakened if reamed cancellous bone remains exposed. Distally migrating the implant to cover all reamed cancellous bone may effectively reduce the abductor moment arm but perhaps this marginal biomechanical alteration is insignificant relative to the risk of femoral neck fracture.

Fracture patterns observed in the three groups are similar to those reported elsewhere in the literature (42;43). Fracture of the resurfacing construct appeared the result of both bending and axial compression in both the Partial and Proud groups resulting in an oblique fracture pattern appearing to initiate at the cortical-cancellous bone interface and exiting the inferior neck proximal to the lesser trochanter. Fracture of the resurfaced femur in the Complete group appeared to initiate in the superior femoral neck adjacent the distal rim of the prosthesis propagating toward the inferior neck in a more vertical, shear-like manner and exiting at approximately the level of the lesser trochanter. Lateralization of the implant decreased the bending moment arm experienced by the resurfaced femur in effect transitioning more of the load to the femur to axial compression.
The current work supports the clinical findings of a potential increased risk of femoral neck fracture following hip resurfacing. Retrospective reviews of patients sustaining femoral neck fracture following hip resurfacing have suggested that neck fracture may be associated with mechanical preparatory factors including failure to fully cover reamed cancellous bone with the femoral component (3;9;10;12-14;16). However, the retrospective nature of these studies makes it difficult to isolate confounding factors, particularly with respect to exposed cancellous bone. There is still some considerable debate as to the exact mechanism leading to femoral neck fracture with some authors suggesting that it may be due to vascular insult rather than simply biomechanical factors (44-46).

The precipitous drop in failure load between the three resurfaced groups does not appear to be adequately explained by a simple increase in femoral implant offset. With a linear increase in offset, one may expect a linear decrease in load-to-failure, however, a linear relationship between load-to-failure and offset was not observed. Increasing the offset by approximately 5 mm, compared to the native femoral head offset, decreased the load-to-failure by 31%. Conversely, decreasing the offset by the same amount increased the failure load by 50%. This may be explained by the disparity in elastic moduli of the femoral component and the supporting bone underlying the implant. In the Partial and Proud groups, much of the prosthesis was supported by reamed cancellous bone. There is a three order of magnitude difference between elastic moduli of the femoral component and the cancellous bone. This abrupt transition in stiffness creates an enhanced shearing effect at the component-bone interface resulting in markedly decreased load-to-failure values. Only an order of magnitude separates the elastic modulus of the femoral component from that of the cortical bone and thus, as the distal rim of the prosthesis is lateralized and uniformly positioned over cortical bone, the decrease in stiffness is less abrupt resulting in a much stronger resurfacing construct and a dramatically increased load bearing capacity of the proximal femur.

The results of the finite element models indicate that exposed, reamed cancellous bone increases peak equivalent strain in the bone compared to the fully seated component condition and that the strain level increases with increasing degree of exposed cancellous bone. Similar work by Long and Bartel showed that placement of the implant at the natural joint center, effectively exposing reamed cancellous bone, increased local bone strain compared to that of a fully seated component covering all reamed cancellous bone (32). The condition of a component seated
proud as the result of an excessively thick cement mantle appears to have the greatest impact on strain levels in the prepared femoral head. Strain in the superior head and neck of the Proud-Thick Mantle model was greater than that of the Proud model with a standard cement mantle thickness despite having equal offsets. This is in contrast to the findings of Taylor who showed that cement mantle thickness had a negligible effect on strain pattern in the prepared femoral head (35). Perhaps, the increased offset of the Proud and Proud-Thick Mantle models exacerbates the effect of cement mantle thickness on strain patterns in the resurfaced femoral head.

The reported benefit of placing an implant in relative valgus orientation was also demonstrated in this study. Orientation of the implant in 10 degrees of valgus relative to the native neck-shaft angle decreased strain in the superior cancellous bone of the prepared femoral head to the order of that of the Complete model in which all reamed cancellous bone was fully covered. Aligning the femoral component in relative valgus appears to diminish superior neck strain and returns strain patterns closer to those experienced in the intact femur (47). The current study also showed that valgus orientation appeared to increase strain in the inferior prepared femoral head and neck. This finding agrees with that of Radcliffe and Taylor (47) who found that while reducing strain in the superior neck, a valgus orientated implant increased strain in the inferior neck. Placing the implant in a relative valgus orientation may elicit a protective effect on the resurfaced femur and therefore it appears prudent to prepare the femur with the implant in a valgus orientation to minimize the detrimental effect of exposed cancellous bone following impaction of the femoral component.

The findings in this study are limited to a basic biomechanical model of the proximal femur and may not precisely replicate the behaviour of bone in vivo. The use of Third Generation Composite Femurs has been well validated as replicating the gross mechanical behaviour of cadaveric bone while avoiding many of the difficulties associated with the use of human specimens including large variations in cadaveric femora geometry, size and bone mineral density (21;22;48). The analogue cancellous bone material used in these femurs is cellular in nature, an improvement over previous generations, however, the behaviour of this material has not been explicitly validated to replicate the behaviour of human cancellous bone and remains a limitation to the use of composite femurs in destructive testing. The absence of hip joint muscle attachments in the mechanical testing construct is an additional limitation as they are believed to
increase compression in the superior neck and as such may have an impact on the current results. In spite of this limitation, it has been reported that under normal gait loading the femur is primarily in a state of axial compression (23;49) with previous literature supporting biomechanical testing conducted under this premise (42;43). The author believes the general trend of the current findings will hold despite the basic nature of the model, however, because no prior studies have conclusively shown that the proximal neck region of the synthetic femurs is equivalent to that of human femurs, the failure loads and fracture patterns in this region as presented currently should be viewed circumspectly.

4.4.6 Conclusion

The new generation of hip resurfacing is gaining increasing acceptance as a treatment option for young and active patients with hip arthritis. With hip resurfacing once again becoming a popular alternative to total hip arthroplasty, optimal preparation of the femoral head is vital in ensuring the integrity of the resurfacing construct in order to avoid increased failure rates due femoral neck fracture. The concerns over femoral neck fracture are substantiated by the weakening of the proximal femur following hip resurfacing. Exposed reamed cancellous bone due to poor or insufficient seating of the femoral component appears to significantly weaken the proximal femur. The perceived benefit of reconstructing the femur to its native geometry may inherently weaken the proximal femur if reamed cancellous bone remains exposed following impaction of the femoral component. Placement of the femoral component in a valgus orientation may diminish the detrimental effect of exposed cancellous bone following implant impaction. Failure to completely cover all reamed cancellous bone may lead to an increased risk of femoral neck fracture following hip resurfacing.

4.4.7 References


5.1 Pre-operative Planning

Pre-operative templating is an important part of the planning process in hip resurfacing as it provides the surgeon an opportunity to optimally plan the size and position of the resurfacing components. The aim of the work in this area was to quantify the accuracy and reliability of anatomical axis, femoral implant inclination and femoral implant size estimation by digital pre-operative template. Estimation of the native neck-shaft angle (NSA) was determined to be less reliable than measurement of the implant stem-shaft angle (SSA). It is thought that the presence of a clearly defined implant stem increases observer reliability in angular assessment of the implant whereas greater interpretation exists when approximating the angle of the native femoral neck as no clearly defined reference from which to gauge the angulation of the neck is present. Femoral malposition during radiography may compound the effect of this measurement variability. Both rotation and flexion of the femur impacted the perceived SSA through clinically achievable ranges of motion and contributed to significant disparities in measurement. External rotation of the femur of greater than 30 degrees or flexion of the femur in excess of 40 degrees should be avoided as this tends toward clinically significant errors in measurement. It is recommended that the patient be positioned with the leg internally rotated and extended to minimize imaging errors. Estimation of the NSA is the basis for determination of the planned implant position and SSA and therefore, accurate and repeatable estimation of the NSA is critical. A more robust method of anatomical axis estimation may be required to ensure proper planning of implant orientation.

Choosing the correct femoral component size is vital to ensuring proper femoral head preparation. Poor component placement has been associated with femoral neck fracture as well as accelerated implant wear and increased blood ion levels in metal-on-metal hip resurfacing. Pre-operative templating was performed on 50 patient radiographs on two separate occasions with the objective of determining the accuracy and repeatability of this method for pre-operative implant selection. Digital pre-operative templating was accurate in determining the correct
implant size in only half of the templates performed. The reliability of pre-operative templating was variable amongst surgeons and only fair between surgeons. There was a tendency to undersize the components if the correct implant size was not chosen. Selection of a smaller femoral component enhances the risk of femoral neck notching and varus implant alignment. These findings emphasize the need for intra-operative verification of pre-operative templating results by way of femoral neck gauge or caliper coupled with meticulous preparation of the acetabulum to ensure proper implant size selection in hip resurfacing.

5.2 Intra-operative Computer Navigation

Computer navigation for hip resurfacing affords the surgeon a means to increase the accuracy and precision of initial femoral guidewire insertion, in turn minimizing the likelihood of femoral head malpreparation. The clinical series of 100 consecutive 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. The post-operative stem-shaft angle differed from the planned stem-shaft angle by only 2.8 degrees on average and in 86% of cases the final stem-shaft angle fell within ±5 degrees of plan. This level of accuracy is felt to be acceptable considering that approximately 10 degrees of valgus alignment is routinely planned. One of the most important roles for computer assisted surgery is in minimizing the surgeon learning curve and reducing the incidence of outliers. A learning curve was observed in the series for navigation time with a significant reduction in the time taken to navigate and insert the initial femoral guidewire between the first 20 cases and the remainder of the series. However, there was no such learning curve encountered for implant placement accuracy. The surgeon was able to immediately achieve and maintain a high level of accuracy for femoral component placement with the use of imageless navigation demonstrating the effectiveness of this tool as a means of optimizing femoral head preparation.

Imageless computer navigation not only shows promise in routine cases of hip resurfacing but also in technically challenging cases that extend the indications for this form of joint replacement. The current work compared implant placement accuracy and navigation time between a cohort of patients with abnormal femoral anatomy or retained hardware to a matched cohort of standard hip
resurfacing patients. The mean deviation of the post-operatively assessed stem-shaft angle from the pre-operative plan was 0.6 degrees with a mean navigation time of 18 minutes. There were no significant differences between patients with abnormal femoral anatomy and matched subjects with respect to stem-shaft angle error (p=0.464) or navigation time (p=0.904). Hip resurfacing is a suitable option for patients presenting with degenerative hip disease second to malformed femoral anatomy or hardware in situ. For appropriate patients, hip resurfacing may eliminate the need for corrective femoral osteotomy or the removal of proximal femoral hardware and the use of computer navigation enhances the accuracy of placement of the femoral component in these patients.

Imageless computer navigation is not yet in wide-spread use and many surgeons rely on conventional mechanical means for alignment and insertion of the initial femoral guidewire. Numerous alignment jigs are currently available, however, there are no clear indications as to which alignment methods or devices provide the surgeon with the most accurate and precise placement of the initial guidewire. The current work looked to compare the performance of several commercially available guidewire alignment jigs with imageless computer navigation. Navigation provided ranges of error in guidewire inclination up to 8 times less than conventional jigs but provided similar ranges of error in guidewire version. Next to navigation, a lateral pin jig provided the most accurate coronal placement of the initial guidewire while a neck centering jig provided the most precise coronal guidewire placement. Correct alignment of the initial femoral guidewire is vital in avoiding malpreparation of the femoral head and choice of alignment device may influence the accuracy and precision of guidewire insertion. Imageless computer navigation provided accurate and precise coronal alignment of the initial femoral guidewire, superior to that of conventional instrumentation, but performed similarly to conventional jigs in femoral guidewire version.

Imageless computer navigation may provide improved levels of accuracy and precision to that of conventional instrumentation; however the efficacy of this tool is dependent on generation of accurate computer models of the patient anatomy. The current work examined the accuracy of computer estimated neck-shaft angle and femoral component size compared to the pre-operative plan and intra-operative verification in a clinical series as well as in bench-side testing. The clinical series showed that the average discrepancy between the measured and computed NSA was 16 degrees with a range of error three times this value. Navigation estimated the measured
neck-shaft angle to within ±3 degrees in only 16 cases while underestimating this parameter in almost 40% of cases. While an overestimated neck-shaft angle may potentially be problematic for femoral head preparation if extreme, underestimation of the axis may lead to varus implant alignment, which has been clinically and biomechanically demonstrated to predispose the resurfaced femur to femoral neck fracture. In both the clinical and laboratory settings, the navigation system tended to overestimate the correct implant size. This phenomenon has negative implications for acetabular bone removal and proper preparation of the femoral head. While the navigation system did not undersize the implant in the laboratory setting, it did in the clinical setting which presents the risk of femoral neck notching if the computed implant size is accepted. This risk of neck notching is enhanced with relative valgus positioning of the implant. Clinically, component sizing should be conducted via a pre-operative template and verified by neck gauge intra-operatively to ensure optimal implant selection. It is imperative that prudent pre-operative planning be used in conjunction with imageless navigation as it appears that misleading information may be registered intra-operatively and could potentially lead to femoral head malpreparation. Strict reliance on data obtained during intra-operative navigation may yield erroneous implant selection and placement and thus a comprehensive pre-operative plan is vital to the success of the procedure utilizing imageless navigation.

5.3 Femoral Head Preparation

Femoral neck fracture is the leading cause for revision in hip resurfacing. A number of femoral neck fracture risks have been identified through retrospective clinical reviews including implant alignment, femoral neck notching and exposed cancellous bone. The current work explored the biomechanical effect of implant alignment using synthetic and cadaveric femora. In synthetic femora with a normal neck-shaft angle (135 degrees), a 10 degree relative varus aligned implant significantly weakened the proximal femur compared to a neutrally aligned component. A relative 10 degree valgus aligned implant did not have an appreciable effect on femoral strength in these normal synthetic femora but did have a significant strengthening effect in synthetic femora with varus native femoral necks (120 degrees). In all synthetic and cadaveric femora tested, a 20 degree relative valgus aligned femoral component significantly strengthened the proximal femur to axial loading compared to neutrally aligned components. Regression analysis
results suggest that retention of the intact proximal femoral strength occurs at an implant angulation of \( \geq 142 \) degrees and the benefit of further valgus alignment may be outweighed in clinical practice by the increased risk of superior femoral neck notching.

Superior neck notching occurs as the result of excessive valgus alignment of the femoral component or inferior translation of the initial guidewire as a result of inaccurate guidewire insertion. The biomechanical effect of superior femoral neck notching was investigated using composite synthetic femora and a finite element model. A 2 mm superior neck notch significantly diminished the load bearing capacity of the proximal resurfaced femur compared to femurs prepared in the absence of notching, and a 5 mm notch further significantly weakened the resurfaced proximal femur. A 2 mm notch represents a superficial breach of the superior cervical cortex, likely undetectable intra-operatively and possibly overlooked post-operatively, whereas a 5 mm superior notch represents a full thickness breach of the superior cortex sure to be detected both intra- and post-operatively. The finite element analysis substantiated the mechanical testing findings showing increasing strain magnitude within the prepared femoral neck in the area of the notch root with increasing notch depth. This work supports preparation of the femoral head in the absence of a superior femoral neck notch to minimize the risk of post-operative neck fracture.

Failure to fully seat the femoral component may result in exposure of reamed cancellous bone at the base of the implant, in turn increasing the potential risk of femoral neck fracture. The current work looked at the biomechanical effect of varying degrees of exposed cancellous bone on fracture resistance in the resurfaced proximal femur. Seating the component at the native femoral head offset, thereby recreating the native anatomy, resulted in partially exposed cancellous bone and significantly reduced the load-to-failure compared to the fully seated component condition. Poor bone preparation or an excessive cement mantle may result in a proud component and a circumferentially exposed ring of cancellous bone. This condition had the greatest impact on fracture resistance, significantly reducing the load-to-failure compared to both the anatomic positioning of the implant and the position of complete cancellous bone coverage. Finite element analysis revealed peak equivalent strain in the reamed cancellous bone of the femoral head increasing with corresponding degree of exposed bone and that placement of the femoral component in a valgus orientation may diminish the detrimental effect of exposed cancellous bone following implant impaction. The perceived benefit of reconstructing the femur
to its native geometry may inherently weaken the proximal femur and increase femoral neck fracture risk if reamed cancellous bone remains exposed following implant placement.

5.4 Conclusions

Hip resurfacing is an alternative to total hip arthroplasty with the goal of conserving femoral bone stock and restoring native hip mechanics. Successful outcomes in hip resurfacing are contingent on a number of patient and surgical factors. Proper patient selection and prudent surgical technique are paramount in avoiding early component failure and the need for re-operation. Hip resurfacing is a process made up of a number of individual operations each potentially having a significant impact on the overall surgical outcome. Femoral neck fracture is a major limitation to this form of joint replacement and is largely preventable by means of proper femoral head preparation. As posited by this thesis, the specific factors that affect femoral head preparation include pre-operative planning, initial femoral guidewire placement and mechanical preparation of the femoral head. The work herein has attempted to elucidate these areas with respect to femoral neck fracture prevention and establish guidelines surgeons may use to optimize surgical preparation of the femoral head.

A pre-operative plan, including templating femoral component size and orientation, is an important first step in optimizing femoral head preparation. Despite showing only moderate repeatability in Chapter 2 for neck-shaft angle measurement and implant selection, the native NSA should be estimated along with placement of a suitable femoral component in an appropriate amount of relative valgus alignment ensuring superior femoral neck notching is avoided. The estimation of these two variables pre-operatively is necessary in order to provide a benchmark against which to verify imageless navigation data intra-operatively. As shown in Chapter 3, there was a tendency for the navigation system to incorrectly estimate the NSA and femoral component size and acceptance of these erroneous approximations may have a detrimental impact on subsequent femoral head preparation. When planning the implant stem-shaft angle, a minimum of 10 degrees of relative valgus is recommended for varus native femoral necks, while varus implant alignment is to be avoided regardless of femoral morphology. As a guide, the implant stem should align roughly parallel to the medial calcar.
Intra-operatively, implant selection should be verified following capsulotomy and subluxation of the femur with the appropriate neck gauge or caliper. As shown in Chapter 2, there was a tendency to underestimate the appropriate size femoral component during pre-operative templating if the correct implant size was not chosen. This may be the result of variation in the magnification of the radiograph; however, this may also be the inherent result of the native geometry of the femoral neck. In an anteroposterior radiograph, the craniocaudal width of the femoral neck can be misleading for determining the femoral component size. The largest diameter of the femoral neck spans between the posteroinferior and the anterosuperior aspects of the femoral neck and this distance cannot be adequately assessed using an AP radiograph. Thus, it is important to use a neck gauge or caliper to verify the correct component size against this portion of the femoral neck. If the correct size implant is not chosen based on this diameter, femoral neck notching is most likely to occur in the anterosuperior neck region.

Upon registration of the patient’s femoral anatomy, navigation generated data should be verified with the pre-operatively determined neck-shaft angle and intra-operatively verified femoral component size. The planned stem-shaft angle should be verified within the computer generated femoral model to confirm the appropriate inclination of the femoral component. Imageless computer navigation provides an accurate and precise method of femoral guidewire insertion and should be used over conventional guidewire alignment instrumentation whenever possible. The femoral head should be prepared in a meticulous fashion and cylindrical reaming should be performed in an iterative manner ensuring superior femoral neck notching is avoided. With the use of electrocautery, the depth of head planing should be accurately marked on the femoral head zenith. This will ensure adequate distal resection of the femoral head and reduce the potential for exposed, reamed cancellous bone. Placing excessive cement in the implant prior to impaction should be avoided as this may result in the implant sitting proud, exposing unsupported, reamed cancellous bone.

Femoral neck fracture has been described as multifactorial in nature (1) and is often the catastrophic result of avoidable surgical error. It is ambitious to believe that the incidence of femoral neck fracture can be entirely eliminated but by incorporating a disciplined approach to femoral head preparation, it is anticipated that the occurrence of femoral neck fracture can be dramatically reduced. Conducting a thorough pre-operative plan, accurately and precisely inserting the initial femoral guidewire, and meticulously resecting the femoral head are all vital
to ensuring optimal femoral head preparation. The work developed in this thesis has brought together benchside investigation of the critical planning and mechanical preparatory factors that may affect the outcome of hip resurfacing arthroplasty with successful clinical implementation and validation of this methodology within the surgical setting. To this end, the process of pre-operative planning, intra-operative navigation and femoral head preparation described has become standard protocol in the senior surgeon’s practice and has been utilized in over 250 hip resurfacing surgeries. The resulting surgical protocol has been successful in preventing the incidence of femoral neck fracture and has become the teaching model for orthopaedic residents and fellows within the author’s institution. 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 femoral neck fracture and ultimately improve patient outcomes following hip resurfacing arthroplasty.

5.5 Future Directions

The work herein has covered many primary 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 the current work that may present promising paths for future investigation.

First, estimation of the native femoral neck-shaft angle and femoral component size are important parameters in the pre-operative templating process for hip resurfacing. However, the current work identified the reliability in neck-shaft angle measurement and femoral component selection to be less than optimal. Investigation into automated templating methods utilizing image analysis techniques may help improve the accuracy and reliability of this process ultimately enhancing prosthesis selection and implantation.

Second, imageless computer navigation provides an attractive option to current conventional instrumentation for insertion of the initial femoral guidewire, however, the current costs of navigation systems present an obstacle to their wide-spread use. Construction of more robust jigs for non-navigated hip resurfacing may provide the surgeon with limited access to computer navigation an accurate and reliable means for guidewire insertion and subsequent femoral head
preparation. Design of mechanical alignment jigs to utilize technologies including laser
guidance may be the ideal solution to merge current technology with conventional
instrumentation for accurate and reliable insertion of the initial femoral guidewire.

Third, as a result of the inaccuracies and disparities demonstrated with the imageless navigation
system, it would be a prudent undertaking to further evaluate, revise and validate the navigation
algorithms currently in use to correct problems with the anatomical axis estimation and
component size selection. This would help to minimize the likelihood of surgeon error as the
result of reliance on inaccurate computer generated data.

Fourth, to ensure an optimal bearing couple in hip resurfacing it is imperative that the acetabular
cup be navigated as well. Acetabular cup malalignment can lead to increased wear rates and
metal ion levels and their associated sequelae and a greater likelihood of femoro-acetabular
impingement leading to early revision. By positioning the cup and femoral components to
optimally articulate with one another, many of the negative aspects of component malalignment
can be avoided. Navigation appears to be the tool to accomplish this task and warrants further
investigation in this area.

Fifth, as younger and more demanding patients seek solutions to hip pain, the number and
variety of bone sparing orthopaedic devices grows. A valuable extension of the work within this
thesis will be in investigating similar bone preserving implants such as mid-head resection
prostheses or mini-stem total hip arthroplasty prostheses to determine if the principles and
guidelines established herein are universal to similar orthopaedic devices or if alternative
guidelines must be established for individual prosthesis types.

Finally, the current work utilized a whole bone validated finite element model for investigation
into the effects of femoral neck notching and exposed cancellous bone. While outside the scope
of this thesis, the creation of a specific validated finite element femoral neck fracture model
would be a valuable tool for further exploration into the mechanisms of peri-prosthetic neck
fracture for study in hip resurfacing as well as with other neck sparing orthopaedic devices.
5.6 References

LIST OF PUBLICATIONS


