Finite Element Analysis of Femoral Neck Stress in Relation to Pelvic Width

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Abstract

Hip resurfacing arthroplasty has been developed as an alternative to traditional total hip arthroplasty, in an effort to minimize the loss of native bone in young patients with symptomatic hip osteoarthritis. Femoral neck fracture following hip resurfacing is a unique complication; several risk factors are associated with this complication, including female gender. In the present study, we used finite element models of the proximal femur to simulate stresses across the femoral neck in pelvis models with varying widths. This analysis demonstrated an increase in hip reaction forces as the width of the pelvis increases, a condition that simulates a resurfacing condition in a female pelvis. This difference in peak stress on the femoral neck may explain the increased incidence of femoral neck fractures seen in female patients following hip resurfacing.

Hip arthritis is a common condition with an increasing prevalence. In 2003, an estimated 330,000 hip arthroplasty procedures were performed in the United States. In recent years, newer techniques for the treatment of symptomatic osteoarthritis of the hip, such as hip resurfacing, are joining the well-established techniques of total hip arthroplasty and hemiarthroplasty.

For young patients with symptomatic hip osteoarthritis, hip resurfacing has been developed as an alternative to traditional total hip arthroplasty in an effort to preserve native bone stock in anticipation of possible future revision surgery. Hip resurfacing has been shown in several studies to allow patients to achieve a higher post-operative activity level compared to standard total hip arthroplasty. With recent advances in metal-on-metal bearing surfaces, hip resurfacing has reemerged as a viable option to potentially improve implant longevity and patient outcomes for young patients with symptomatic hip degenerative disease.

Femoral neck fracture is a unique complication following hip resurfacing, with reported rates ranging from 0% to 17%. Several risk factors have been associated with post-resurfacing femoral neck fractures, including both patient and surgical factors. Fractures typically occur in the first few months, and the mean time to fracture has been reported as 15.4 weeks following the procedure and are responsible for up to 60% of early revisions. Various surgical risk factors have been shown to increase the potential for femoral neck fracture, among which are the surgeons experience with the technique, incomplete seating of the femoral component, notching of the superolateral femoral neck, and varus placement of the femoral component. Patient related risk factors include age, body mass index (BMI), gender, poor bone quality, large femoral cysts, and osteonecrotic bone.

In a study by Marker and colleagues, cumulative fracture incidence was 2.3% in males versus 6.2% in females (p = 0.02) at 75-months of follow-up. Shimmin and associates presented the Australian experience with Birmingham hip resurfacing and reported a 1.5% incidence of postoperative femoral neck fracture among almost 3,500 resurfacing procedures performed between 1999 and 2003. In this study, the investigators reported that their female patients had almost twice the risk of femoral neck fracture of their male counterparts with a relative risk compared to males of 1.949 (p < 0.01).

In an effort to protect against the possibility of catastrophic failure in the form of post-operative femoral neck fracture, pre-clinical tests need to be developed to test the postoperative physical therapy protocols used following hip...
resurfacing arthroplasty. For these tests to be developed, patient-specific data correlating anatomical variations to the stress levels seen within the femoral neck are necessary. Finite element analysis (FEA) is a viable method to obtain the data of stress distributions throughout the entire femoral neck, within the predetermined anatomical boundary conditions.

Currently, there are no studies in the English literature that correlate the increased risk of femoral neck fractures seen in females and the differences in the bony anatomy of the pelvis between males and females.

Our intention is to use FEA models of the proximal femur to simulate the stresses across the femoral neck in models of varying pelvic width. This data can be extrapolated to predict mechanical failure of the femoral neck following resurfacing arthroplasty. Prior studies have validated the use of FEA models of hip reconstruction relative to bone surface strains. The aim of the present study was to further derive the relationship between the reaction forces seen at the femoral neck and the geometry of the pelvis through application of FEA. We hypothesized that femoral neck stresses would increase with greater pelvic width, a condition that simulates a resurfacing arthroplasty condition in a female pelvis.

**Materials and Methods**

Finite element analysis modeling was performed using computed tomography (CT) models of the left femur consisting of the cortical and cancellous bone portions obtained from the virtual bone database (Munich University, Germany). The models were converted to CAD files (Pro/Engineer Wildfire v2.0 Parametric Technology Corporation, Waltham, MA) and then assembled. These models were subsequently imported into ANSYS Workbench v11.0 (ANSYS Inc., Canonsburg, PA) (Fig. 1). The cortical bone properties were assumed to be isotropic and linearly elastic. The Poisson ratio was 0.3 for both cortical and cancellous bones. The Young’s modulus for cortical bone was 17 GPa and for cancellous bone was 570 MPa. The insertion of the abductor musculature was selected on the lateral and superior surface of the greater trochanter. The calculated abductor muscle force was applied to two identical femoral models one for a narrow pelvis and the second for a wide pelvis. The femoral joint reaction forces, which were based on the calculation of the two pelvic conditions, were applied to the hemispherical surfaces of the femoral heads. A standard body weight (B) of 2,446 N was used for our modeling. The maximal principal stresses were then plotted along the proximal femur.

Boundary conditions were as follows: The magnitudes (R) and angles (A) of the hip joint reaction forces and the abductor muscle forces were determined as a function of pelvic width over the abductor muscle moment arm (a/b) by the following calculation: assuming one legged stance with one leg weighing 1/7th of body weight.

From the moment equilibrium equation about the acetabular center:

\[
\frac{6}{7}B \cdot a = A \cdot b
\]

Where \(B\) is body weight, \(a\) is the distance between the body centerline to the hip center, \(A\) is the abductor force, and \(b\) is the moment arm of \(A\) to the hip center.

Therefore:

\[
A = \frac{a}{b} \cdot \frac{6}{7} \cdot B
\]

The reaction force \(R\) acting on the femoral head is:

\[
R_x = A \sin \theta
\]

\[
R_y = B + A \cos \theta
\]

Where \(B\) is the foot reaction force in one-legged stance.
and is in the same magnitude as the body weight. $\theta$ is the angle between the abductor muscle force and the vertical axis. Thus:

$$R = (Rx^2 + Ry^2)^{0.5} = B \cdot ((a/b \cdot 6/7 \cdot \sin \theta)^2 + (1 + a/b \cdot 6/7 \cdot \sin \theta \cos \theta)^2)^{0.5}$$

Two conditions were tested, the first representing a narrow pelvis ($a/b = 2$) and the second representing a wide pelvis ($a/b = 4$). The corresponding hip reaction forces and abductor muscle forces are:

Narrower pelvis:
$$R = 1.66B, \text{ R angle from vertical: } 20.7^\circ, A = 1.7B, \theta = 20^\circ$$

Wider pelvis:
$$R = 2.41B, \text{ R angle from vertical: } 29.2^\circ, A = 3.4B, \theta = 20^\circ$$

The narrow and wide pelvic boundary conditions were applied to two identical femurs with identical abductor muscle insertions. The distal condyles were fixed in a three dimensional model. Maximum principal stresses were plotted for the entire femurs for both the narrow and wide pelvis models.

Results

The reaction forces acting on the femoral head in the different pelvis models were found to be significantly different. The finite element analysis demonstrated an increase in hip reaction forces as the width of the pelvis increased. In the wider pelvis model, the reaction force on the femoral head was 2.41 times body weight compared to 1.66 times body weight in the narrower pelvis model.

Figures 3 and 6 represent the hip reaction force in both the narrow and wide pelvic models, respectively. A narrower pelvis reduced the reaction forces on the femoral neck compared to that seen with a wider pelvis.

Our analysis showed that when we plotted the maximal principal stress on the femoral neck in both the narrow pelvis model $a/b = 2$ (Figs. 2 and 3) and for the wide pelvis model $a/b = 4$ (Figs. 4 and 5), we observed a significant increase in the principal stress over the posterior-superior aspect of

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**Figure 2** Maximum principal stress distribution on the proximal femur for the narrow pelvis model.

**Figure 3** Maximum principal stress along the neck and head junction for the narrow pelvis model.

**Figure 4** Location of the stress line, which was plotted for the narrow pelvis model.
the femoral head neck junction in the wide pelvis model compared to the narrow pelvis model.

Stress lines were plotted on the femoral neck, for both the narrow and wide pelvis models (Figs. 4 and 7, respectively). The stress lines correspond to the principal stress areas shown in the both pelvis models, both stress lines show a similar area of maximum stress, which corresponds with the posterior-superior head neck junction of the femur.

The wider pelvis model showed increased distribution of the maximum principal stress around the proximal femur. In the posterior-superior femoral neck region, the peak maximum principal stress was 1.7 times higher in wider pelvis model \((a/b = 4)\) than the peak maximum principal stress in the narrow pelvis model \((a/b = 2)\) (Fig. 8).

**Discussion**

Hip resurfacing with preservation of the femoral head and neck is an attractive concept for treatment of end-stage arthritis in the young, active patient population. Suggested benefits of resurfacing include better joint stability, improved proprioception, and a reduced risk of leg-length discrepancy.\(^{20}\)

Historically, aseptic loosening of the acetabular component is the major cause of failure following total hip arthroplasty. With the increased popularity of hip resurfacing procedures, postoperative femoral neck fracture has become a significant procedure-related complication.

Fractures of the neck of the femur have long been recognized as a major complication following resurfacing.\(^{20,23}\) Capello coworkers\(^{24}\) and Freeman and associates\(^{25}\) reported femoral neck fracture incidence as high as 18% and 25%, respectively. Current resurfacing series report a much lower incidence of femoral neck fractures, ranging between 0% and 2.8%.\(^{5,10,11,26,27}\) The Australian experience reported by Shimmin and associates\(^{11}\) showed an incidence of femoral neck fractures of 1.46% with a higher relative risk for females.

The increased incidence of femoral neck fractures after resurfacing is most likely due to a doubling of the tensile stress across the upper part of the femoral neck.\(^{28}\) No study
Comparison of the hip reaction force as a function of $a/b$

Figure 8 Comparison of the hip reaction force as a function of $a/b$.

...to date has correlated the increased risk for femoral neck fracture seen in females and the anatomical difference of the female pelvis compared to the male pelvis.

In concordance with our hypothesis, we demonstrated that when we plotted the maximal principal stress on the femoral neck in both the narrow pelvis model, and for the wide pelvis model, we can observe a significant increase in the principal stress over the posterior-superior aspect of the femoral head neck junction in the wide pelvis model compared to the narrow pelvis model.

Anatomic studies have shown that the compressive strength of the femoral neck relies on the medial trabecular system. In the wider pelvis model, increased tensile stresses occur at the posterior-superior cortex, which increases the medial compressive forces present and allows shear stresses to develop at the prosthesis-neck junction. A narrower pelvis reduces the load on the femoral neck compared to that seen with a wider pelvis and thus reduces the risk for femoral neck fracture. We have demonstrated that in a wide pelvis model, the peak maximum principal stress was 1.7 times higher than the peak maximum principal stress in the narrow pelvis model. This difference in peak stress on the femoral neck can help explain the increased incidence of femoral neck fractures seen in females following hip resurfacing arthroplasty.

Our findings are limited to a finite element model of the femur and pelvis and may not replicate the behavior of bone and muscle in vivo. Further work is needed to evaluate the effect of different loading regimens, the specific effect of muscle forces, and comparison of the models to clinical data.

Conclusion

The present study demonstrated a correlation between femoral neck peak stresses and pelvic width. This difference in maximum principal stress in the wide pelvic model compared to the narrow pelvic model may explain the increased incidence of femoral neck fractures in females compared to males.

Disclosure Statement

None of the authors have a financial or proprietary interest in the subject matter or materials discussed, including, but not limited to, employment, consultancies, stock ownership, honoraria, and paid expert testimony.

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