Biomechanics of the Birmingham hip resurfacing arthroplasty

The effects of the method of fixation and interface conditions on the biomechanics of the femoral component of the Birmingham hip resurfacing arthroplasty were examined using a highly detailed three-dimensional computer model of the hip. Stresses and strains in the proximal femur were compared for the natural femur and for the femur resurfaced with the Birmingham hip resurfacing. A comparison of cemented versus uncemented fixation showed no advantage of either with regard to bone loading. When the Birmingham hip resurfacing femoral component was fixed to bone, proximal femoral stresses and strains were non-physiological. Bone resorption was predicted in the inferomedial and superolateral bone within the Birmingham hip resurfacing shell. Resorption was limited to the superolateral region when the stem was not fixed. The increased bone strain observed adjacent to the distal stem should stimulate an increase in bone density at that location. The remodelling of bone seen during revision of failed Birmingham hip resurfacing implants appears to be consistent with the predictions of our finite element analysis.

The theoretical advantages of hip resurfacing when compared with total hip replacement (THR) include minimal resection of the femoral head and improved joint stability. Resurfacing may load the proximal femur in a more physiological manner, thereby reducing bone loss due to stress shielding.

The most widely-used hip resurfacing arthroplasty has been the Birmingham hip resurfacing (BHR) model (Smith & Nephew Orthopaedics Ltd, Bromsgrove, United Kingdom) and both short- and medium-term results have been published. Bone resorption was predicted in the inferomedial and superolateral bone within the Birmingham hip resurfacing shell. Resorption was limited to the superolateral region when the stem was not fixed. The increased bone strain observed adjacent to the distal stem should stimulate an increase in bone density at that location. The remodelling of bone seen during revision of failed Birmingham hip resurfacing implants appears to be consistent with the predictions of our finite element analysis.

Materials and Methods
A 3D finite element model of the natural bilateral pelvis, sacrum and left femur was generated based on the geometry and material properties of a cadaver hip (45-year-old woman with no known bone disorder; ScienceCare...
Anatomical, Phoenix, Arizona). Images of 1 mm slices of the hip (523 slices in total; in-plane resolution of 0.781 mm x 0.781 mm) and of a bone mineral density calibration phantom (European Spine Phantom, QRM; GmbH, Möhrendort, Germany) were obtained using a computed tomography (CT) scanner (Toshiba Aquilion, 120 kVp; Toshiba America Medical Systems, Tustin, California). Ethical approval of the protocol for acquisition and imaging of the pelvis was obtained.

The quantitative CT data were used to segment the anatomical surfaces. A finite element mesh of the natural hip was generated using TrueGrid software (XYZ Scientific Applications Inc., Livermore, California). Linear brick elements were used to model the pelvic, sacral and femoral trabecular bone, and linear shell elements were used to model a 1 mm thick cortical shell around the pelvis. The final mesh consisted of 272 992 brick elements and 37 008 shell elements, with 292 744 nodes (Fig. 1). Adequate mesh refinement was verified by convergence analyses.

The model was in good agreement with previously reported stresses and strains for the hip. The load transfer patterns and stresses produced in the natural hip finite element model were similar to the in vitro contact stresses of up to 11.7 MPa (SD 2.1) at 200% to 300% body-weight loads. Similarly, the von Mises stress distributions in the natural pelvis agreed with those computed in previous 3D finite element models of the pelvis. The surface strains for the intact femur were also consistent with experimental strain gauge and photoelastic strain results.

Birmingham hip resurfacing finite element models with a 52 mm outer diameter acetabular component and a 46 mm outer diameter femoral component were also constructed (Fig. 1). The acetabular and femoral component models had 13 824 elements (15 993 nodes) and 42 752 elements (47 763 nodes), respectively. The acetabular component was orientated in 45° abduction and 15° anteverison. To simulate optimum uncemented fixation, it was assumed that the component was bonded perfectly to the surrounding bone. In order to allow the ‘implantation’ of the femoral component, the natural femoral head model was partially resected and chamfered, and a channel through the femoral neck was created for the stem. The femoral component was aligned with a stem-shaft angle of 136°, consistent with the average alignment of implanted hip resurfacing prostheses (Fig. 2). The component-head diametral clearance was assumed to be 80 µm. The BHR finite element model comprised 286 720 brick elements and 32 822 shell elements, with 315 173 nodes.

Non-homogeneous isotropic, linear elastic material properties were assigned to the trabecular bone in the natural hip and BHR finite element models based on the quantitative CT data and density-modulus relationships. The BHR acetabular and femoral components models were assigned material properties for high carbon cast cobalt-chromium. A detailed summary of the material properties in the finite element models is given in Table I.

A parametric analysis of the BHR arthroplasty was performed to examine the effects of femoral component fixation (cemented versus uncemented) and femoral bone-implant interface fixation (bonded head and stem versus

![Fig. 1](image1.png)

Three-dimensional finite element meshes of the natural hip (a to c) and the Birmingham hip resurfacing (d to g), including anterior (b) and lateral (c) views of the natural femur, the Birmingham hip resurfacing acetabular component (e), Birmingham hip resurfacing femoral component (f), and anterior view of the chamfered and resected femur (g).

![Fig. 2](image2.png)

Coronal cross-sections of the uncemented (left) and cemented (right) Birmingham hip resurfacing finite element models.
bonded head and sliding (loose) stem versus sliding (loose) head and stem. Although the current BHR design relies on cemented fixation, uncemented fixation was also examined to evaluate its feasibility and impact on the transfer of stress and strain to the proximal femur. In addition, for a technically well-inserted implant the BHR head is well fixed (‘bonded’) and the stem is not fixed (‘sliding’ or loose), which corresponds to a bonded head and a sliding stem interface condition. The remaining two sets of interface conditions, bonded head-bonded stem and sliding head-sliding stem, reflect hypothetical circumstances of fixing the stem and complete loosening of the implant, respectively.

A total of five BHR finite element models were generated (Table II). Three models incorporated uncemented femoral components that corresponded to the three femoral bone-implant interface conditions stated above. The remaining two models simulated cemented femoral components with a cement layer (polymethylmethacrylate) approximately 2 mm to 2.5 mm thick adjacent to the chamfered edges of the resected femoral head. The femoral head was assumed to be perfectly bonded to the cement layer for the cemented BHR models; the stem was assumed to be either perfectly bonded or sliding (µ = 0.3). The static and dynamic coefficient of friction at the interface between the femoral and acetabular components of the BHR was assumed to be 0.15.

Distal femoral loads and moments were applied at the mid-diaphyseal region of the femur to simulate joint loading during walking. The distal femoral loads and moments were extrapolated from static equilibrium, with an assumed peak joint reaction force of 3000 N applied through the centre of the femoral head and 1620 N abductor muscle loads applied at the greater trochanter. In addition to the distal femoral loads, the forces of 22 muscles attached to the left pelvis and the abductor force attached to the greater trochanter were also taken into account. The magnitudes of the muscle forces were scaled to correspond to a peak joint reaction force of 3000 N. The muscle forces were applied as distributed nodal loads at the insertion sites.

The finite element models were analysed using an explicit finite element analysis software, LS-DYNA (Livermore Software Technology Corporation, Livermore, California). Each model was analysed on three to six dual AMD Opteron processor (2 × 2.4 GHz) workstations (AMD, Sunnyvale, California) and required approximately 335 to 445 Central Processing Unit (CPU) hours for each analysis. Maximum compressive (minimum principal) stresses and yield (von Mises) strains in the proximal femur were compared for the BHR and natural hip models. An initial site-specific internal bone remodelling stimulus for the BHR hips was also evaluated, whereby site-specific changes in strain energy of more than 75% for the BHR femur relative to the natural femur would predict remodelling. In this mode a positive change causes formation and a negative change resorption.

**Results**

In the natural femur, stress was transferred from the superior femoral head through the centre of the head to the medial trabecular column (Fig. 3; top row). The presence of cement under the femoral head in the cemented BHR models did not alter the stress patterns compared to the uncemented models. Irrespective of interface conditions, the BHR femurs showed a different stress transfer pathway. In the presence of an implant, superolateral stress shielding was evident, with stress transfer from the femoral stem to the medial cortex rather than from the superior head to the cortex. The level of stress shielding was greatest when the femoral head and stem were both fully bonded to bone. The stress patterns in the resurfaced hip were most nearly ‘physiological’ when both the head and the stem were not attached to the adjacent bone (sliding head and sliding stem).

The von Mises strain in the natural femur exhibited larger strain fields from the superior femoral head and along the medial trabecular column, with similar distribution of the stresses (Fig. 3; middle row). In both the uncemented and cemented BHR models, strain was generally reduced in the superolateral regions of the resected femoral head. The strains also decreased in the inferomedial head of the resurfaced models compared to the natural hip. There were minimal differences in femoral bone strain between...
the cemented and uncemented BHRs under comparable interface conditions. Strain shielding was especially noticeable when the femoral loading platform was bonded to bone. The presence or absence of stem bonding had little effect on this condition (bonded-sliding and bonded-bonded). When the stem was allowed to slide, localised peaks in strain were present along the medial bone-stem region as well as around the tip, whether or not the loading platform was bonded (bonded-sliding and sliding-sliding conditions). In addition, localised strain peaks occurred along the chamfered head of the uncemented BHR when the entire femoral component was debonded (sliding-sliding).

Under comparable interface conditions there were no differences in bone remodelling between the cemented and uncemented BHRs. Initial bone resorption was predicted in the superolateral femur for all BHR models, except for the debonded uncemented implant (Fig. 3; bottom row). There was also additional resorption of inferomedial femoral bone when the stem was bonded. Bone formation was predicted around the distal stem for all cases. This extended more proximally when the stem was not fixed to bone.

**Discussion**

Our study provides high-resolution stress and strain fields around the femur, incorporating the inhomogeneous CT-based distribution of bone properties obtained from a relatively young donor. This represents the target population for hip resurfacing replacements such as the BHR. However, as with previous finite element results, our findings are limited by the reliance on a single subject and on the assumption of isotropy of the properties of cancellous bone.

The finding of femoral bone stress shielding around the femoral component of the BHR is consistent with previous computational analyses of hip resurfacing replacements.18-20 For example, using a finite element model of a cemented McMinn femoral component (Smith & Nephew, London, United Kingdom), Watanabe et al20 found a small degree of stress shielding in the anterosuperior femoral head region. Stress concentrations were also located near the inferior portions of the stem and tip of the stem in their model, and were probably caused by implant toggling and stem bending. Although their finite element model of this component did not simulate the inhomogeneity of the bone material properties, the resultant trends reported were consistent with our study. The greatest bone resorption was predicted in the superolateral and inferomedial portions of the femoral head of the current model when both the head and stem were fixed owing to the stress and strain transfer through the stem, instead of the proximal head. However, these effects were reduced when the stem was loose, limit-
ing bone resorption only to the superolateral head. In contrast, Huiskes et al\textsuperscript{18} investigated the load transmission and interface stresses in a finite element model of the stemless Wagner resurfacing replacement and concluded that bone resorption would most likely occur along the peripheral head-neck region and in the central part of the femoral head. These differences may be explained by the incorporation of the mini-stem in the BHR design.

This study has illustrated the effects of various bone-implant interface conditions for the BHR arthroplasty. Similar effects of interface bonding on bone stresses have been reported for both conventional THR and hip resurfacing replacements.\textsuperscript{17,27} The predicted distal bone formation is also consistent with a recent densitometric study that observed changes in bone density around the BHR hips \textit{in vivo}.\textsuperscript{8} However, the proximal bone changes predicted by our study were not identified in this previous dual energy x-ray absorptiometry study\textsuperscript{8} owing to the screening effect of the metallic implant, which limits measurements of bone mineral density within the femoral head. Retrievals of resurfacing components have confirmed osteoclastic activity in the femoral head immediately underlying the loading platform,\textsuperscript{18,39} and the concurrent phenomena of proximal bone resorption and distal bone formation in resurfaced hips\textsuperscript{40} are similar to the predicted remodelling results.

The BHR was positioned at a single stem-shaft angle in our models. However, radiographic assessments of hip resurfacing femoral components have shown a large range of orientation, from 110° to 170°.\textsuperscript{1,6,12,16,41} The clinical consequences of extreme valgus or varus positioning of the femoral component is still unclear. Amstutz et al\textsuperscript{41} reported a significantly higher incidence of revision for femoral loosening in hips with more varus orientation, and Shimmin et al\textsuperscript{14} described varus placement in 42 of 50 (84%) cases of femoral neck fracture. Conversely, others have reported no adverse effects in patients with more varus components.\textsuperscript{12,14,41} Further work will be required to elucidate the biomechanical consequences of malalignment of the femoral component and to identify whether the finite element model offers further insight into complications that have been reported in these circumstances.\textsuperscript{11,39}

It has been suggested that preparation of the femur for resurfacing can compromise epiphyseal vascularity and bone viability,\textsuperscript{10,15} leaving the layer of bone adjacent to the loading platform vulnerable to osteonecrosis, particularly if not infiltrated with bone cement. In such circumstances the stem would provide the sole means of support for the components. In thinner-stemmed resurfacing devices, such
loading conditions may cause fatigue fracture at the stem-shell junction (Fig. 4). Although the bulkier stem of the BHR may prevent such failure, direct transmission of stress and strain through the stem may lead to failure of fixation and loosening (Fig. 5). These scenarios were not modelled in the current analysis and will require iterative bone remodelling studies with concurrent epiphyseal osteonecrosis.

These finite element analyses provide an understanding of the effects of various factors on the biomechanics of the BHR arthroplasty and femoral head resurfacing devices of similar design. Although the study does not predict failure of the BHR femoral component, it does suggest that mechanically induced bone remodelling is probable. Specifically, the superolateral and inferomedial bone within the femoral head is at risk. Furthermore, the stem will provide the primary route for transfer of load to the cortical bone of the distal femoral neck. Hence, it may be anticipated that bone will remold around the stem of the femoral component and this provides a plausible mechanism for the reported incidences of neck thinning.\textsuperscript{3,5,39} Whether such remodelling has an influence on the longevity or performance of these devices will require careful long-term clinical review and retrieval studies.

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