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Bone remodelling inside a cemented resurfaced femoral head

Sanjay Gupta [a,b,*], Andrew M.R. New [a], Mark Taylor [a]

[a] Bioengineering Science Research Group, School of Engineering Sciences, University of Southampton, Highfield, Southampton S017 1BJ, United Kingdom

[b] Department of Applied Mechanics, Bengal Engineering and Science University, Shibpur, Howrah 711 103, West Bengal, India

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Abstract

Background. Although the short-term performance of modern resurfacing hip arthroplasty is impressive, the long-term performance is still unknown. It is hypothesised that bone remodelling and the resulting changes in stress/strain distribution within the resurfaced femur influence the risk of fixation failure.

Method. Three-dimensional finite element models and adaptive bone remodelling algorithms have been used to predict long-term changes in bone density following cemented femoral head resurfacing. Applied loading conditions include normal walking and stair climbing. The remodelling simulation was validated by comparing the results of an analysis of a proximal femur implanted with a Charnley femoral component with known clinical data in terms of bone density adaptations.

Findings. Resurfacing caused a reduction of strain of 20–70% in the bone underlying the implant as compared to the intact femur, immediately post operative. Elevated strains, ranging between 0.50 and 0.80% strain, were generated post-operatively around the proximal femoral neck regions, indicating a potential risk of neck fracture. However, this strain concentration was considerably reduced after bone remodelling. After remodelling, bone resorption of 60–90% was observed in the bone underlying the implant. Reduction in bone density of 5–47% occurred in the lateral femoral head. Bone apposition was observed in the proximal–medial cortex, around the inferior edge of the implant. Hardly any changes in bone density occurred in the distal neck or the femoral diaphysis.

Interpretation. Although resurfacing has produced encouraging clinical results, bone remodelling within the femoral head might be a concern for long-term fixation. Regions of strain concentration at the head–neck junction, which may increase the initial risk of femoral neck fracture, are reduced with bone remodelling. In order to reduce this risk of femoral neck fracture, patients should avoid activities which induce high loading of the hip during the early rehabilitation period after surgery.

Keywords: Resurfaced femur; Bone remodelling; Finite element analysis; Bone density

1. Introduction

The resurfacing hip arthroplasty has several advantages over conventional total hip arthroplasty (THA) that include minimal bone resection, easier revision, and reduction in stress shielding in the proximal femur. A resurfacing procedure produces a more physiological stress distribution than the conventional stemmed hip replacement (Daniel et al., 2004). Experience with cement fixed resurfacing femoral components has been excellent, although small series of hydroxyapatite coated femoral components have also shown good results (McMinn et al., 1996). The cement fixation method offers more versatility in treating patients with misshapen femoral heads, large bone cysts, or avascular necrosis (McMinn et al., 1996). Although the short-term performance of modern resurfacing hip arthroplasty is impressive, long-term performance is still unknown (McMinn et al., 1996). Moreover, there is a concern of emoral neck fracture due to high strains in the proximal

* Corresponding author. Address: Biomechanics Division, Department of Mechanical Engineering, Imperial College London Exhibition Road, South Kensington, London SW7 2AZ, United Kingdom.

E-mail address: sguptabec@yahoo.com (S. Gupta).

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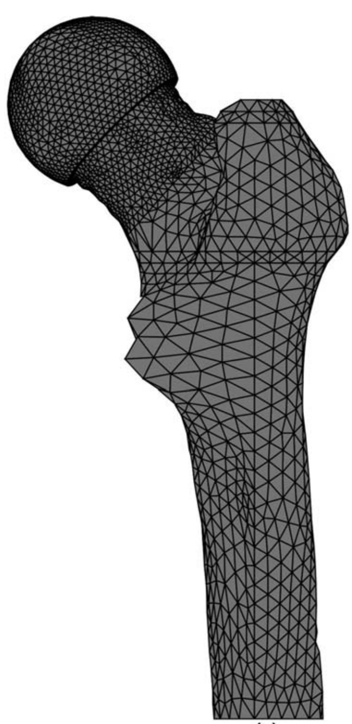
femoral neck (Watanabe et al., 2000). Stress shielding inside the femoral head might also lead to bone remodelling, affecting the long-term fixation of the implant. Currently there are relatively a few biomechanical studies on stress related fixation failure of resurfacing hip arthroplasty as compared to the conventional THA (Watanabe et al., 2000; Vena et al., 2000; McMinn et al., 1996). Vena et al. (2000) presented a preliminary study on numerical design optimisation of a resurfacing prosthesis, using a relatively simple two-dimensional (2D) plane strain finite element (FE) model of the femoral head. The study, however, does not include the extent of bone remodelling, its effect on the stress/strain pattern and the risk of fixation failure. While investigating the load transmission and interface stresses in the Wagner resurfaced femoral head, Huiskes et al. (1985) hypothesised that the femoral resurfacing component was more sensitive to local loosening than other prostheses. Their hypothesis indicated that prosthetic designs should be analysed relative to their potential to provoke failure propagation, rather than only initiation of mechanical failure and loosening.

It may be assumed that stresses and strain generated within the resurfaced femur, immediately post-operative and after bone remodelling, affect short-term and long-term survival of the resurfacing procedure. Hence, it is necessary to investigate the extent to which the effect of bone remodelling and the gradual changes of stress/strain distribution relate to the eventual risk of fixation failure. Computer simulations of adaptive bone remodelling in combination with FE models of natural and implanted bone structures have been used to predict stress shielding and long-term adaptations of bone density within the reconstructed joint (Weinans et al., 1993; Huiskes et al., 1992; van Rietbergen et al., 1992; Huiskes et al., 1987). Using 3D FE models of the intact (natural) and the resurfaced femur, the aims of this study were to investigate: (1) the strain distribution in the resurfaced femoral head before and after bone remodelling, (2) the extent of bone remodelling around a cemented resurfaced femoral head, with regard to short-term and long-term risk of fixation failure.

2. Materials and method

2.1. FE models of intact and implanted proximal femurs

Three-dimensional FE models of an intact right proximal femur and a proximal femur with resurfaced femoral head (Fig. 1a) were developed using computed tomography (CT) scan data and the solid modeller of ANSYS (ANSYS Inc., PA, USA) FE software. The femur was implanted with a 44 mm diameter femoral head resurfacing prosthesis (ASR, DePuy International, Leeds, United Kingdom), as shown in Fig. 1b. The inner surface of the implant was fixed to the bone using bone-cement (PMMA). The tapered stem was inserted into a parallel side hole and was modelled as completely debonded. The Young's modulus for the PMMA and the implant were assumed to be 2500 and 235 000 MPa, respectively. A Poisson's ratio of 0.3 was assumed for all materials. Ten-node tetrahedral solid elements were used for mesh generation. The FE models of the intact and the implanted femur contained 68 946



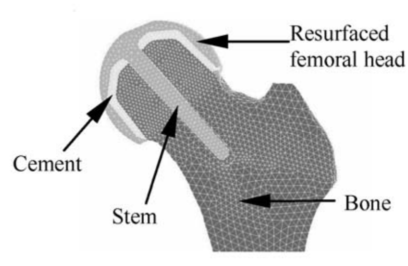


Fig. 1. Finite element model of the resurfaced femur, (a) full model; (b) a mid-frontal enlarged view of the surgical construction.

elements, 98 671 nodes, and 295 899 degrees of freedom. Mesh generation and solutions were obtained using ANSYS. Bone was assumed to a linear isotropic material. The Young's modulus (E in MPa) and apparent density (ρ in g cm^{-3}), were allocated to each bone element using the CT-scan data and the relationship, $E = 7281\ \rho^{1.52}$, using Bonemat software (Zannoni et al., 1998).

2.2. Applied loading conditions

Musculoskeletal loading plays an important role in the biological process of bone remodelling. Data on musculoskeletal loading conditions during normal walking and stair climbing for a number of patients were presented by Heller et al. (2001). These loading conditions were applied to the FE model as two static load cases. In the remodelling simulation these load cases were assumed to have equal frequency. The body weight was assumed to be 70 kg. Applied loads consisted of the hip contact force and forces simulating the abductor, tensor fascia lata, vastus lateralis and vastus medialis muscles and illo-tibial tract (Heller et al., 2001). These loads were uniformly distributed over the area of contact (for the hip joint reaction force) or the estimated muscle insertion sites (muscle forces). Nodes located on the distal end of the femur were constrained in all directions (Fig. 1).

2.3. Adaptive bone remodelling numerical simulation

The adaptive bone remodelling theory used in this study used a site-specific formulation. The remodelling rate (rate of change of bone density) was related to the difference ($S - S_{ref}$) between the remodelling signal (S) of the implanted bone and the equilibrium or reference stimulus (S_{ref}) of the intact bone (van Rietbergen et al., 1992). The S and S_{ref} are the local (per element) elastic strain energy per unit bone mass averaged over a loading history, for an implanted and an intact femur, respectively (van Rietbergen et al., 1992). In reality, bone is unresponsive to small deviations from the reference stimulus, so a 'dead zone' was incorporated (van Rietbergen et al., 1992). The dead zone was taken as ± 0.75 of S_{ref} (Huiskes et al., 1992; Engh et al., 1992a). The iterative process of calculating the strain distribution in the bone and then updating the bone density based on the strain distribution after implantation of the prosthesis was continued until a new equilibrium density pattern was reached. The upper and lower bounds of bone density were set to 1.73 or 0.01 g cm^{-3}, respectively (Huiskes et al., 1992).

The differences in strain between the intact femur and the resurfaced femur were obtained to assess the effects of the resurfacing procedure. Strain was preferred to stress, as trabecular bone has been reported to have a uniform yield strain within a given site regardless of variation in bone density, elastic modulus and yield stress (Morgan and Keaveny, 2001). Normalised values of peak strain in the resurfaced femur were calculated relative to that of the intact (natural) femur immediately after surgery and then after every five iterations of the bone remodelling procedure until a new state of equilibrium was achieved after 50 iterations.

2.4. Qualitative validation of the bone remodelling simulation

The authors are not aware of any clinical data on the changes in bone density within the resurfaced femoral head. However, bone remodelling in the proximal femur after Charnley THA has been extensively reported (Cohen and Rushton, 1995; Engh et al., 1992a; Engh et al., 1992b; Weinans et al., 1993; McCarthy et al., 1991). In order to validate the numerical simulation, the same technique was applied to a FE model of a proximal femur implanted with Charnley femoral component. Following a similar procedure to that given above (Sections 2.1–2.3), 3D FE models of an intact right proximal femur and the same femur with a cemented Charnley femoral component were developed. The resulting changes in bone density predicted by our numerical simulation were compared with the data from the clinical studies on bone remodelling with Charnley femoral component listed above.

3. Results

Von Mises equivalent strain and bone density distributions under both loading conditions were obtained before implantation, in the immediate post-operative situation and after the new equilibrium in bone density had been achieved after 50 iterations. Post-operatively, strain shielding was observed inside the proximal femoral head. Reduction of strain between 20 and 70% was observed in the superior femoral head as compared to the intact femur (Figs. 2 and 3). During normal walking, reductions in strain of 20–70% were observed within the femoral head (Fig. 2a and b). However, the resurfacing procedure lead to elevated strains of 0.50–0.70% around the superior neck regions (Fig. 2b), particularly around the rim of the prosthesis. Bone remodelling results in considerable reduction of strains to 0.30–0.40% in this area of high strain concentration (Fig. 2c). Similar changes in strain distribution around the superior rim of the prosthesis were observed in the case of stair climbing, as indicated in Fig. 3a–c. During stair climbing high strain concentrations, 0.60–0.80% strain, were observed post-operatively, which were reduced to 0.40–0.50% with bone remodelling (Fig. 3).

Peak strain througout the bone remodelling process is presented in Fig. 4, where normalised peak strains in the resurfaced femur are plotted against number of iterations. It should be noted, post-operatively, that there is a sharp increase in the peak strain, to about 1.56 times that of the intact femur, generated in the trabecular bone around the superior femoral neck in the resurfaced femur. However, with gradual changes in bone density this peak strain value was reduced to 0.9 times that of the intact femur, stabilising after around 10 iterations (Fig. 4).

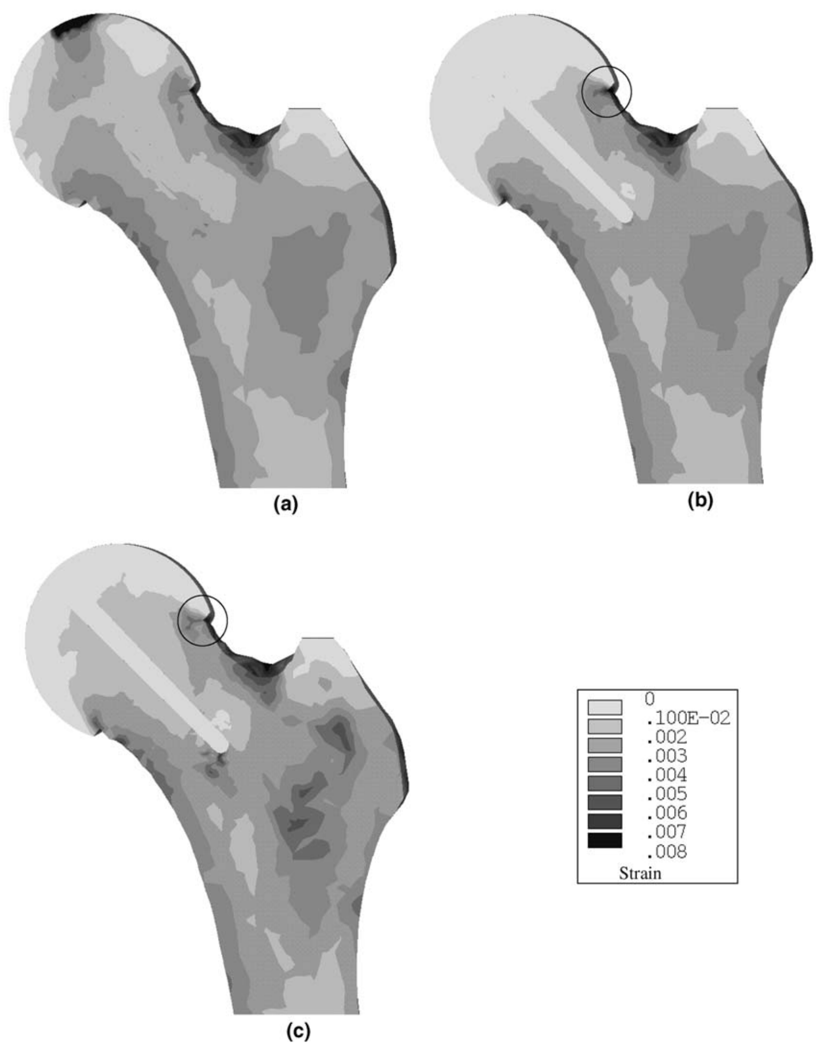


Fig. 2. A mid-frontal view of the Von Mises equivalent strain distributions during normal walking within, (a) an intact femur; (b) a resurfaced femur immediate post-operative; (c) a resurfaced femur after equilibrium in bone remodelling (after 50 iterative steps). ○: Location of high strain concentration (b); reduced considerably after bone remodelling (c).

Strain shielding caused changes in bone density within the resurfaced femoral head. Bone density immediately post-operatively and after every ten iterative steps is presented in Fig. 5. Within the distal neck and the diaphysis of the femur, there were hardly any changes in bone density, indicating little or no remodelling. After 50 iterative steps substantial bone resorption was found within the resurfaced femoral head and around the proximal part of the stem. Bone density reductions between 60 and 90% as compared to the intact femur were observed in the region underlying the resurfaced head, indicating significant bone resorption. Towards the lateral side of the femoral head this change in bone density ranged between 5 and 47%. However, some bone apposition (densification) was observed in the proximal–medial cortex, adjacent to the inferior tip of the implant. This trend in bone remodelling was consistent with increase in iterative steps until equilibrium in density pattern was attained after 50 iterations.

Bone remodelling in the proximal femur after Charnley THA has been used to validate the numerical simulation. In this case, equilibrium in bone density pattern was attained after 60 iterative steps. Post-operatively, the bone density distribution is presented in Fig. 6a. The changes in bone density after 60 iterative steps is indicated Fig. 6b. Substantial bone resorption occurred in the proximal part of the implanted femur, whereas bone densification occurred around the distal tip of the implant (Fig. 6b). Results indicated up to 40% reduction in bone density in the proximal–medial region, and up to 20% reduction in bone density in the proximal lateral region as compared to the immediate post-operative density distribution (Fig. 6). From the proximal to the distal end of the implant, bone resorption was reduced to a maximum of 10% (Fig. 6). Around the distal tip of the implant, significant bone apposition up to 40% was observed as compared to the immediate post-operative density distribution (Fig. 6). These results compared very well with the clinical

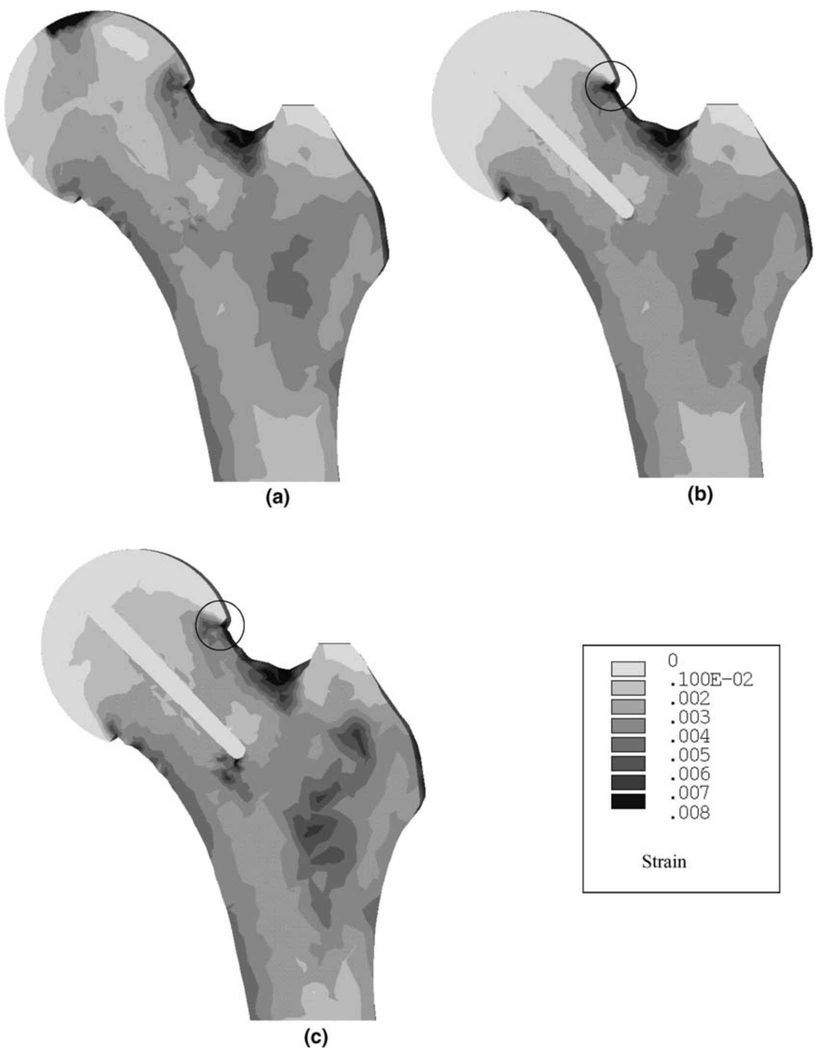


Fig. 3. A mid-frontal view of the Von Mises equivalent strain distributions during stair climbing within, (a) an intact femur; (b) a resurfaced femur immediate post-operative; (c) a resurfaced femur after equilibrium in bone remodelling (after 50 iterative steps). ○: Location of high strain concentration (b); reduced considerably after bone remodelling (c).

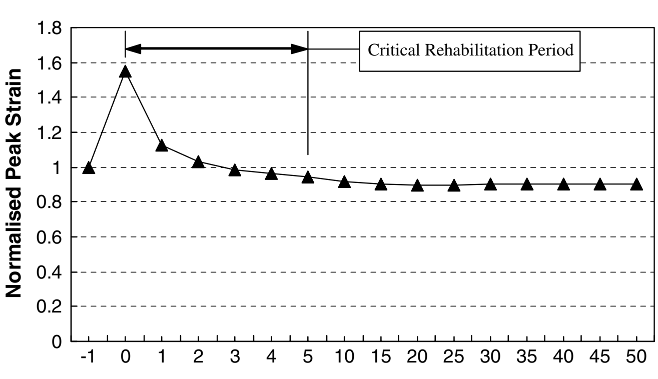


Fig. 4. Normalised peak strain plotted against number of iteration for the resurfaced femur. The iteration number −1 corresponds to the intact femur, whereas the iteration number 0 corresponds to immediate post-operative scenario. (Normalised strain in the trabecular bone of the resurfaced femur were calculated relative to the intact femur.)

observations of bone remodelling in the proximal femur after Charnley THA.

4. Discussion

The study was aimed at investigating the short-term risk of femoral neck fracture and the long-term risk of failure of fixation inside a resurfaced femoral head due to evolutionary changes in bone density and strain distribution. One of the main objectives of using a resurfacing prosthesis as compared to conventional hip arthroplasty is that the pattern of loading of the proximal femur after resurfacing is more physiological than with a conventional stemmed replacement (Daniel et al., 2004). The results of this study certainly support this concept. However, results indicated strain shielding within the femoral head. In this study, this strain shielding lead to bone remodelling and consequently 50–90% reduction in bone density in the superior femoral head region.

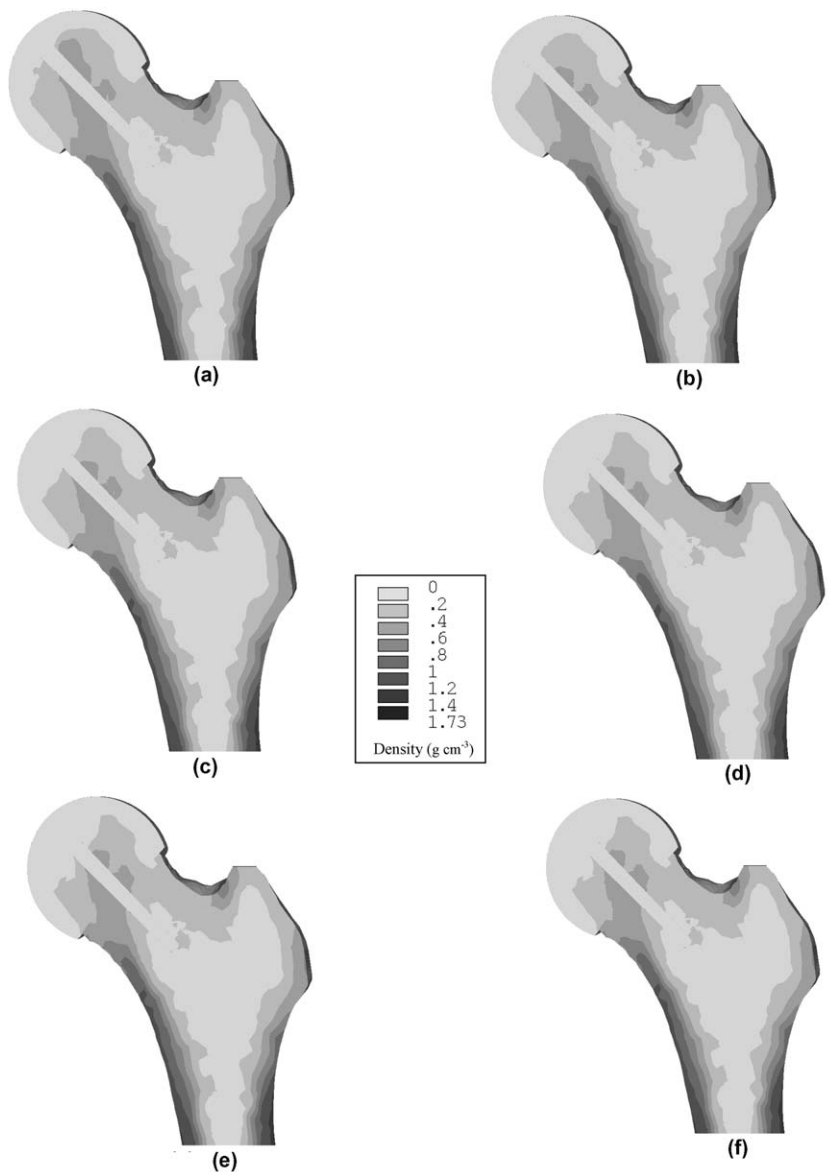


Fig. 5. Bone density distributions in a resurfaced femoral head, mid-frontal view. (a) Immediate post-operative; (b) after 10 iterations; (c) after 20 iterations; (d) after 30 iterations; (e) after 40 iterations; (f) after 50 iterations.

Short-term follow-up studies (12–24 months) on Birmingham hip resurfacing (BHR) indicate that it is an inherently stable device (Glyn-Jones et al., 2004). Daniel et al. (2004) observed 99.7% survival out of a total of 403 hips with a maximum follow-up-period of 4.8 years, with a consecutive series of young patients (aged less than 55 years) with osteoarthritis. Their study suggests that metal-on-metal hip resurfacing is very effective for end-stage arthritis in this age group. McMinn et al. (1996), while reviewing 235 resurfaced hips over 5 years, reported that metal-on-metal resurfacing hip replacements with cement fixed femoral components have been performing excellently at short follow-up. Despite these encouraging results with the resurfacing procedure, substantial bone remodelling within the femoral head might be a concern for long-term the fixation of this implant.

Another point of concern about the resurfacing procedure is the risk of femoral neck fracture. In this study elevated strains of 0.50–0.80% were generated in the bone of the superior femoral neck (Figs. 2 and 3). These peak strains, however, account for a small volume of bone, indicating a very low risk of fracture. Morgan and Keaveny (2001) reported that the mean compressive yield strain of human trabecular bone ranged from $0.70 \pm 0.05\%$ for the trochanter to $0.85 \pm 0.10\%$ for the femoral neck; mean tensile yield strains ranged from $0.61 \pm 0.05\%$ for both the femoral neck and trochanter to $0.70 \pm 0.05\%$ for the vertebra. By comparing our results with these yield strain values, it appears that there is a small risk of local failure in the femoral neck region post-operatively, if the patient is subject to high loads arising due to normal physiological activities, in particular stair climbing. However, this strain

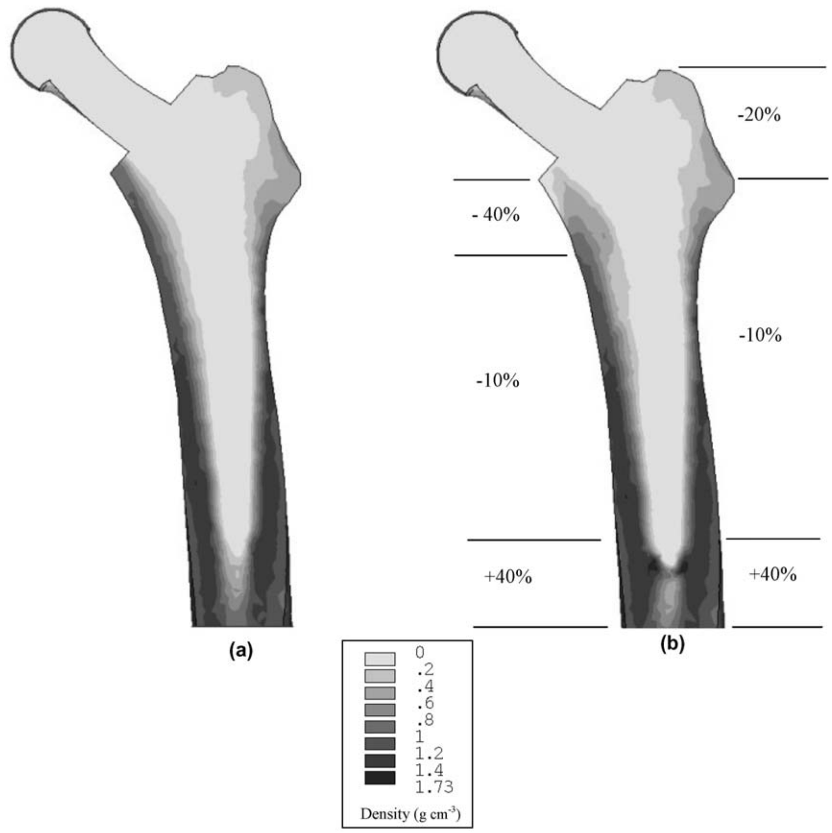


Fig. 6. Bone density distributions in a proximal femur implanted with a Charnley femoral component, mid-frontal view. (a) Immediate post-operative; (b) after equilibrium in bone remodelling (after 60 iterations). The negative sign indicates bone resorption, whereas the positive sign indicates bone apposition.

concentration was considerably reduced with bone remodelling, thereby lowering the risk of failure, significantly. Clinical results indicate similar trends, wherein either a femoral neck fracture occurred immediately after the resurfacing procedure, or not at all. Clinical evidence suggests that in majority of patients this should not be an issue. However, in patients with poor bone quality, there may be increased risk of femoral neck fracture (Watanabe et al., 2000). Moreover, this behaviour of sharp increase in strain of about 1.56 times that of the intact femur, followed by reduction in strain due to bone remodelling, suggests that a cautious approach should be undertaken for the patient during the rehabilitation procedure, as designated by the 'critical rehabilitation period' in Fig. 4. During this period, patients should abstain from performing physiological activities that might generate high musculoskeletal loads on the resurfaced femur, in order to reduce the initial risk of femoral neck fracture.

4.1. Comparison with other studies

The numerical predictions of our study agree well with others (Watanabe et al., 2000; Vena et al., 2000; McMinn et al., 1996; De Waal Malefijt and Huiskes, 1993; Orr et al., 1990; Phillips et al., 1987; Huiskes et al., 1985). Significant strain shielding with 20–70% reduction in strain as compared to the intact femur were observed in the trabecular bone underlying the implant. The results of Watanabe et al. (2000) demonstrated similar stress shielding in the anterosuperior region of the femoral neck, directly beneath the prosthesis. Additionally, our findings were qualitatively consistent with those of Vena et al. (2000), De Waal Malefijt and Huiskes (1993) and Orr et al. (1990). Although the major effects of stress shielding beneath the loaded part of the metallic implant were observed, the study by Vena et al. (2000) does not include the evolutionary bone loss or gain and its relationship with eventual risk of fixation failure. Huiskes et al. (1985) reported occurrence of unnatural stress patterns in the femoral head and at the implant–bone interfaces, enhancing interface failure and bone remodelling. However, these stresses were not higher than those reported for other kinds of prostheses, e.g., the acetabular cup or knee replacement tibial component (Huiskes et al., 1985). Phillips et al. (1987) found completely or partially resorbed superior femoral heads in sheep with resurfaced hips. There have been no reports on femoral neck fractures and dislocations in 235 resurfaced femurs over 5 years, although thinning in the femoral neck was observed in some patients after surgery (McMinn et al., 1996). However, the relationship between stress shielding and thinning in the femoral neck is not precisely known. It may be concluded that the results of our study are believed to be more accurate since the numerical simulations were based on reasonably accurate 3D FE models and realistic musculoskeletal loading conditions.

This method of predicting changes in bone bensity around an implant is based on Weinans et al. (1993). The method however, has a number of limitations. Bone geometry and density distribution were based on CT-scan data of one representative femur and bone was assumed to be a linear and isotropic material. The relationship between the iterative time step involved in the predictions of bone density, and actual time, in months or years, is not known. Comparison of these results with DEXA scans involving human femoral specimens would lead to more precise validation and would allow iterative time step size to be related to physical time step size.

4.2. Validation of the numerical simulation

In order to validate these numerical results, the numerical simulation of bone remodelling was applied to a FE model of a proximal femur implanted with Charnley femoral component. Results indicated substantial bone resorption at the proximal region and bone densification at around the distal tip of the implant (Fig. 5). Bone resorption increased from the distal to the proximal part of the femur, in particular around the proximal–medial side (maximum 40% bone loss) and around the proximal lateral side (maximum 20% bone loss). These findings are very well supported by other studies (Cohen and Rushton, 1995; Engh et al., 1992a; Engh et al., 1992b; McCarthy et al., 1991). Cohen and Rushton (1995) reported that at 12 months post-operative stage, the overall pattern of change in bone mineral density (BMD) was of resorption increasing from the distal to the proximal part of the femur, with apposition below the tip of the prosthesis. During the first six months, all the other regions on either side of the prosthesis showed a reduction in BMD, while the shaft of femur distal to the tip of the implant did not change (Cohen and Rushton, 1995). From 6 to 12 months, the BMD increased below the tip and medial to the distal third of the prosthesis (Cohen and Rushton, 1995). At one year after operation there was a mean 6.7% reduction in BMD in the region of the calcar and a mean 5.3% increase in BMD in the femoral shaft distal to the tip of the implant. However, their study was restricted to 12 months follow-up-period. Engh et al. (1992a) measured periprosthetic bone mineral content (BMC) and cortical strain in five specimens of the uncemented AML prosthesis (DePuy, Warsaw, Indiana) studied at up to 7.5 years after surgery. They compared the BMC in six regions around the prosthesis with comparable regions in the intact femur, and found a gradient bone loss, highest proximally and lower around the middle third. They associated these remodelling changes with strain shielding of the cortex. Further analysis of the data obtained from the DEXA scans (Engh et al., 1992b) showed a mean loss of 45% of BMC around the proximal third and 32% around the middle third. Around the distal third of the implant, three of the five cases showed no bone loss, one showed some loss, and one had an increase in BMC. McCarthy et al. (1991) in a retrospective study of cemented THA's, showed a substantial reduction in BMC in 3 years after operation. They showed average loss of 40% in the proximal–medial part, which decreases from the proximal to the distal side. It appears therefore, that the changes in bone density around the Charnley femoral component as predicted by our study correlate well with similar studies. It may be concluded that the numerical simulation used in this study has been proved to be useful in predicting bone remodelling inside a cemented resurfaced femoral head.

5. Conclusions

Based on the numerical study, it may be concluded that the resurfacing procedure resulted in strain shielding within the femoral head. Strain shielding leads to substantial bone resorption in the region underlying the resurfacing prosthesis. However, bone apposition was observed in the proximal–medial cortex, around the inferior edge of the implant. Hardly any changes in bone density occurred in the distal femoral neck or the femoral diaphysis. Since resurfacing components generated elevated strains in the superior neck regions, particularly around the superior rim of the prosthesis, there is an initial risk of femoral neck fracture. This strain concentration was considerably reduced after bone remodelling, thereby lowering the risk of femoral neck fracture. A cautious approach should be undertaken during the rehabilitation period, wherein the patient should abstain from performing any physiological activities, such as full weight bearing, that might evoke high musculoskeletal loading conditions on the resurfaced femur.

Acknowledgements

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