Hindawi Publishing Corporation
Research Letters in Materials Science
Volume 2008, Article ID 368985, 4 pages
doi:10.1155/2008/368985

Research Letter

Biomimetic Composite-Metal Hip Resurfacing Implant

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Received 7 April 2008; Accepted 18 June 2008

Recommended by Steve J. Bull

Hip resurfacing technique is a conservative arthroplasty used in the young patient in which the femoral head is reshaped to accept metal cap with small guide stem. In the present investigation, a hybrid composite-metal resurfacing implant is proposed. The cup is made of carbon fiber/polyamide 12 (CF/PA12) covered with a thin layer of cobalt chrome (Co-Cr). Finite element (FE) method was applied to analyze and compare the biomechanical performances of the hybrid hip resurfacing (HHR) and the conventional Birmingham (BHR). Results of the finite element analysis showed that the composite implant leads to an increase in stresses in the cancellous bone by more than 15% than BHR, indicating a lower potential for stress shielding and bone fracture and higher potential for bone apposition with the HHR.

1. INTRODUCTION

The successful reintroduction of the improved metal-on-metal (MOM) bearings has led to a resurgence of interest for hip resurfacing procedure as a viable alternative to conventional arthroplasty for younger and more active patients [1, 2]. The reported benefits of hip resurfacing (HR) include reduced dislocation rate and increased function compared to total hip arthroplasty (THA) [3, 4]. Other advantages of HR compared with THA include minimal bone resection, easier revision, and reduction in the stress shielding in the proximal femur [1, 5].

Femoral neck fracture and stress shielding problems remain a concern with resurfacing hip prostheses [6, 7]. Currently, most implants for joint replacements including HR are manufactured from stiff materials (i.e., stainless steel, Co-Cr, etc.). These materials undergo stress shielding that may lead to implant loosening and femoral neck fracture [8].

Currently, conventional implants still undergo problems of biomechanical mismatch of elastic modulus and interfacial stability with host tissues. Fortunately, fiber-reinforced polymer composites provide an interesting solution to face these problems since they have excellent mechanical properties, such as high fatigue and creep resistance, rigidity, and stiffness. Moreover, these materials have rapid, versatile, and inexpensive fabrication processes.

The feasibility of the proposed biomimetic polymer composite was previously used to manufacture a hip stem for THA. This hip stem described by Campbell et al. [9] and Bougherara et al. [10] was evaluated numerically and experimentally. Preliminary tests investigating the biocompatibility of the biomimetic composite stem showed that the composite produced no adverse cytotoxic response in the periprosthetic tissues [11, 12], and tests using simulated body fluid conditioning showed that the hydroxyapatite- (HA) coated composite has excellent potential of biocompatibility [13].

This new biomimetic composite implant has the ability to mimic the functions of the natural bone that will allow stable fixation of prosthesis with minimal bone loss through stress shielding. The biocompatibility of this new biomimetic composite was verified [14, 15]. Miniature implants made of the same materials and of HA-coated Ti as control were produced and inserted as femoral intramedullary implants in rabbits. Hystomorphometric results for both composite and control implants (HA-coated Ti) showed that the composite implants were highly osseoinductive, by more than one order of magnitude with respect to control (implant coverage exceeding 100% of nominal implant perimeter). The protocol used here thus led us to conclude that the HA-coated PA12/CF composites have the potential to lead to very good osseoconduction that may reduce stress shielding leading to bone resorption.

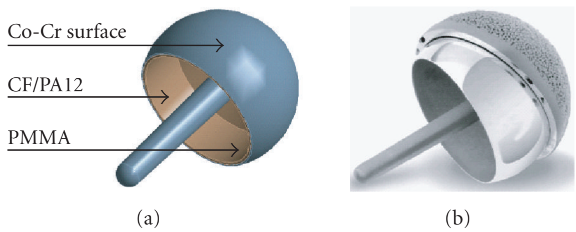

Figure 1: Hip resurfacing. (a) Hybrid HR and (b) Birmingham HR.

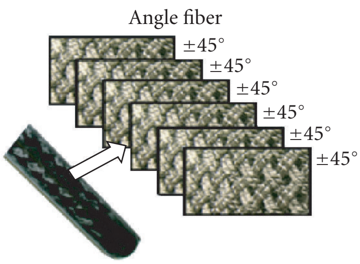

Figure 2: Composite (CF/PA12) stem braided $(+45/-45)_6$.

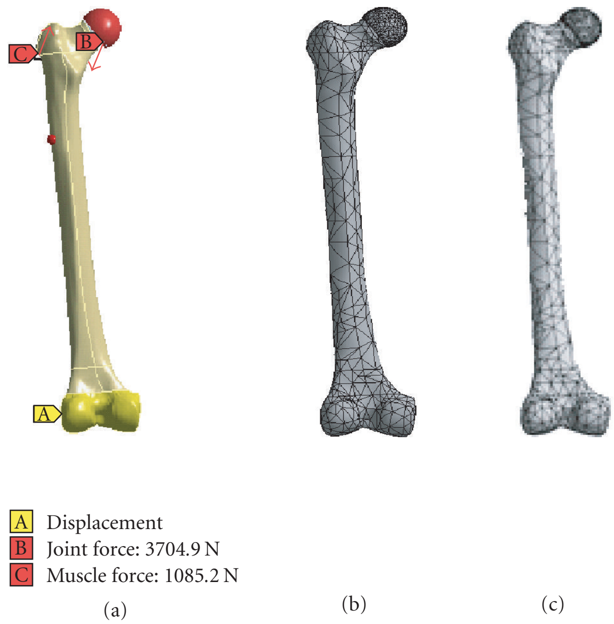

Figure 3: (a) Geometry and load conditions, (b) FE model of BHR, and (c) FE model of HHR.

A novel hybrid composite Co-Cr hip resurfacing (HHR) implant is proposed to prevent stress shielding and bone fracture. The aim of this article is thus to present the concept design for the hybrid resurfacing implant and secondly, to compare its performance to conventional Birmingham hip resurfacing (BHR).

2. MATERIAL AND METHODS

2.1. Concept design and 3D geometries

Computerized tomography (CT) scan sections were performed every 0.5 mm along the length of the composite femur (sawbones 4th generation composite bone models) and used to generate the 3D solid model of the proximal femur [16] (see Figure 2(a)). The elastic modulus of the simulated cortical (short fiber-filled epoxy) and cancellous (rigid polyurethane foam) based on ASTM D-638, D-695, and D-1621 tests were equal to 16.7 (GPa) and 206 (MPa).

The concept and geometry of the hybrid resurfacing component are shown in Figure 1. The femoral cup with a diameter of 46 mm (Birmingham) is composed of 2 mm-thick shell structure made of several layers of continuous carbon fiber/polyamide 12 (CF/PA12) composite fabrics (see Figure 2), onto which a 1 mm layer of Co-Cr is overlaid in order to avoid wear debris formation. The guide stem is composed of the same material as the cup (i.e., CF/PA12-Co-Cr). The cup is fixed to the femoral head with 1.5 mm cement made of PMMA.

2.2. Finite element models

3D FE models of a composite femur were meshed and analyzed using ANSYS 11.0 software. The femoral head was

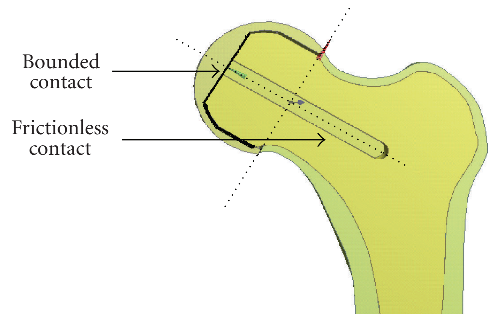

Figure 4: Type of contact used in the FEA.

reamed and embedded with two types of hip resurfacing implants. The first was a model of the femoral bone in which the implanted HR was made of a Cr-Co-base alloy (E = 200 GPa, ν = 0.3) (see Figure 3(b)), while the second was the hybrid composite (CF/PA12) metal (Co-Cr) implant (see Figure 3(c)).

The material properties used for the analysis are shown in Table 1.

The models were meshed with 10 node quadratic tetrahedron elements (see Figure 3(b)). Bonded contact was assumed at the cup-bone interfaces in view of simulating full bone ingrowth and perfect cement fixation. This resulted in a rigid link between the composite cup and the PMMA contact surfaces, allowing no relative sliding or gap opening. The bone-stem interface was simulated using frictionless contact allowing free sliding (see Figure 4).

For each FE model, the load corresponded to 8 running and consisted of a 3704 kN load applied to the femoral head and a 1085 kN great trochanter muscles load [17]. The

Table 1: Mechanical properties of the bone-implant system.

Material	Modulus of elasticity (GPa)	Shear modulus (GPa)	Poisson's ratio
CF/PA12	$E_x = 15.4$	3.	.3
	$E_y = 15.4$	3.5	.3
	$E_z = 3.5$	3.2	.3
PMMA	$E = 2.$	—	.3
Cortical bone	$E = 16.7$	—	.3
Cancellous bone	$E = .206$	—	.3

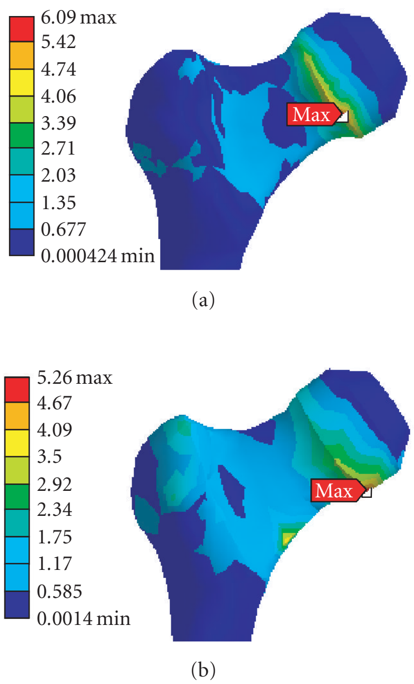

Figure 5: Von Mises stress in the cancellous bone using (a) BHR implant and (b) HHR.

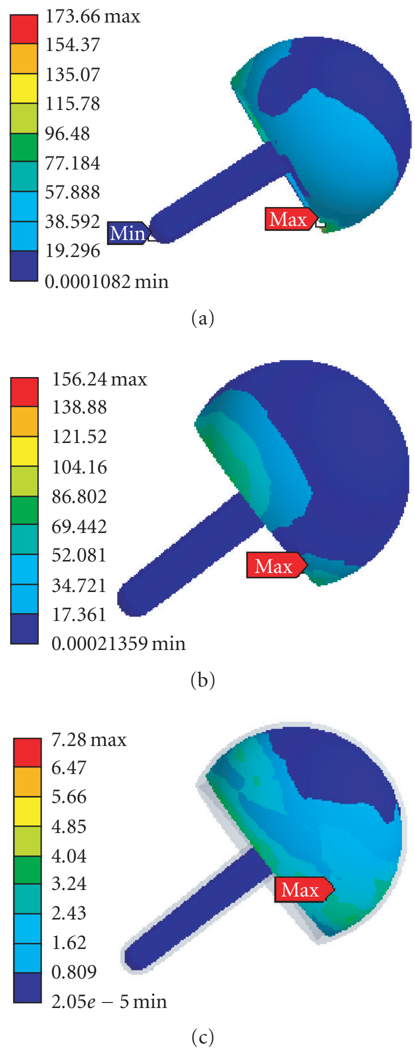

Figure 6: Von Mises stress in the implant using (a) conventional (BHR), (b) hybrid (HHR), and (c) stress distribution in the CF/PA12 shell.

loads were distributed over several nodes to avoid stress concentration, and for all FE analyses, the displacement of all nodes at the distal end of the femoral bone was rigidly constrained (Figure 3(a)).

3. RESULTS

3.1. *Stresses in the trabecular bone*

The von Mises stresses in the trabecular bone with the Cr-Co and CF/PA12 resurfacing implants are shown in Figure 5. The stress inside the trabecular bone was higher for the conventional Co-Cr resurfacing implant (von Mises stress between 0 and 4.7 MPa) than the one using the hybrid CF/PA12-Co-Cr (von Mises stress level ranged between 0 and 4.1 MPa). The highest stress patterns were noted in the posteroinferior region near the rim of the implant. Peak stresses were 6.09 MPa for the Co-Cr prosthesis and 5.26 MPa for the hybrid HR.

3.2. *Stresses in the implant*

The values of stresses in the conventional Co-Cr implant ranged between 0 and 77 compared to 0 and 69 MPa when the hybrid implant is used (see Figure 6(a)). The peak stress in the conventional implant was higher (173.6 MPa) than that found in the hybrid implant (156.2).

4. DISCUSSION

The new concept design for hip resurfacing using a hybrid composite metal was described. Finite element analysis has been performed to evaluate and analyze the potential of the proposed design concept.

In the case of the hybrid implant, numerical results have shown that the von Mises stresses were more uniform and higher by more than 15% in the cancellous bone. This indicates the potential of the hybrid composite implant to reduce stress shielding, especially in the great trochanter region. Also higher peak stress in the cancellous bone was found when the Co-Cr is used, which may lead to one fracture. Again the use of the hybrid implant reduced considerably the peak bone stress in the cancellous bone and thus prevents from bone fracture.

Results of simulation indicate also that the hybrid implant reduced the stress in the femoral cup by approximately 10 to 20%. Therefore, more loads are transferred to the bone with the hybrid composite Co-Cr resurfacing implant than the conventional ones.

The main objective of the current work was to present a preliminary study on the metal composite femoral component. However, the FE model needs some improvements, such as the inclusion of the load bearing surfaces (i.e., acetabular cup). The thickness of this acetabular cup would be expected to affect the load transfer across the bearing surfaces.

5. CONCLUSIONS

The outcome of this study showed that the hybrid composite metal hip resurfacing had the potential to reduce stress shielding, preserve bone stock, and prevent from bone fracture compared to conventional metallic hip resurfacing implants.

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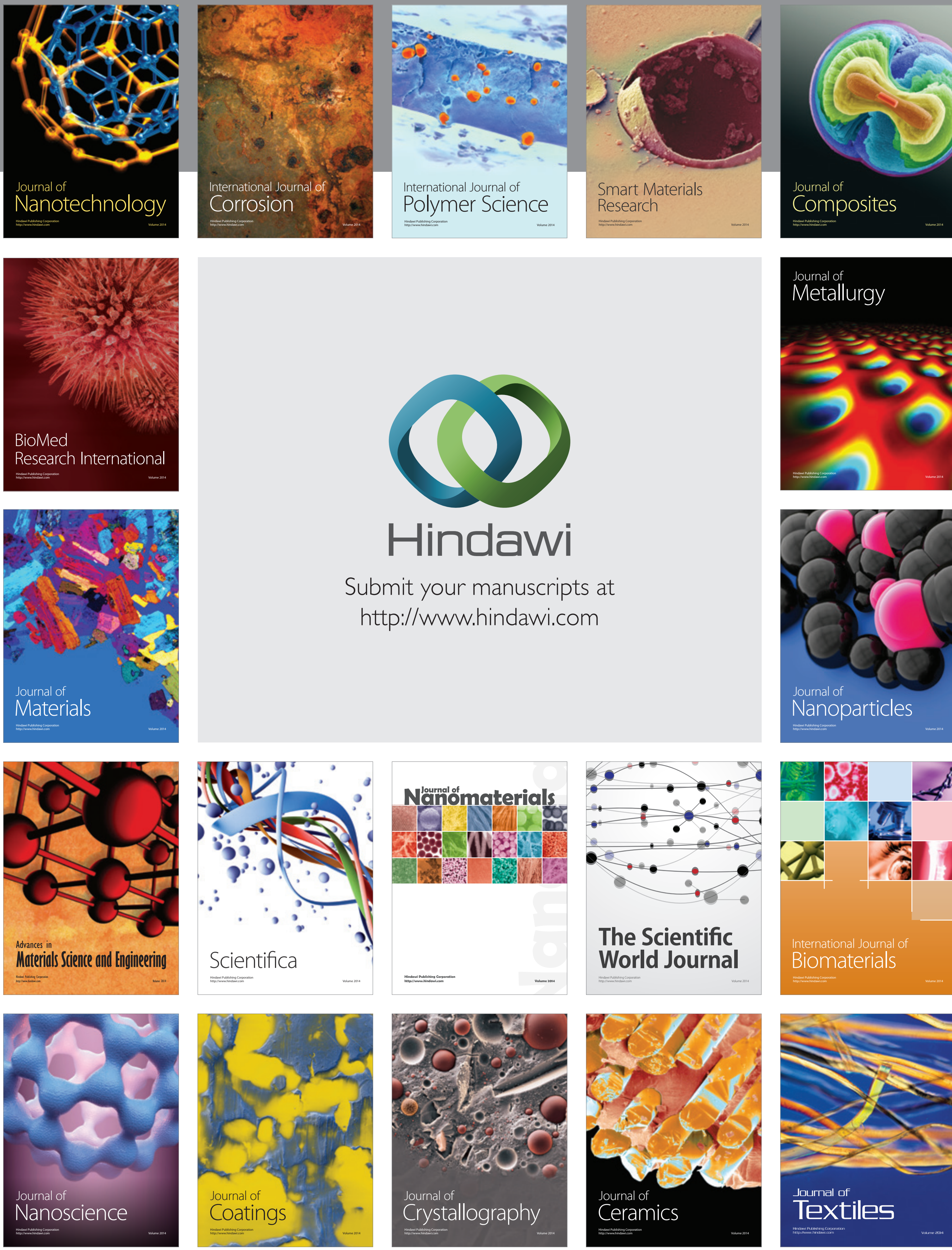

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