Study On A Novel Hip Joint Replacement Surgical Technique

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INTRODUCTION

The hip joint is a ball and socket type joint that consists of the ball-shaped femoral head, two layers of articular cartilage, the acetabular ligament, and the acetabulum socket [1]. Its major function is to maintain body balance and support body weight in both static and dynamic postures, including walking, running, and etc.

Osteoarthritis (OA) is one of the most common causes of THR. It stems from the softening and loss of articular cartilage, leading to the loss of congruity and subtle instability of hip joints. This loss of articular cartilage can eventually cause direct bone-to-bone contact between the femoral head and acetabulum, which results in bone spurs and pain, accompanied by joint disability and reductions in life quality.

Total hip replacement (THR) involves surgical removal of the diseased ball and socket and replacing them with a ball and stem that is inserted into the femur bone and an artificial cup socket. THR works to help patients with severe OA restore their natural movement [2]. However, despite its extremely high successful rate with an average lifespan of approximately 15 years, current THR has certain drawbacks, including device failure caused by femoral stem fracture, acetabular cup wear, and bone density loss caused by stress shielding. Therefore, with the help of a surgeon from UC Davis, we are researching the possibility of developing a new surgical technique that restores the functionality of a degenerated hip joint.

This surgical technique is specifically designed for patients with severe degenerated hip articular cartilage. It involves the surgical removal of the degenerated part of the femoral head and replacing it with the corresponding healthy femoral head portion from a donor. Mating surfaces of the both parts are surgically cut so they form a compatible fit, acting as a fixture mechanism. Ideally, this surgical technique works like a bone graft: after a certain period of bone regeneration, the two parts fuse together. As this surgical technique is still at its proposal state, the feasibility is unclear. Therefore, our study aims to use finite element analysis (FEA) to help investigate the feasibility of this surgical technique by looking at the stress states of the postoperative hip joint from different fixture designs under different mechanical loading states.

METHODS

Two models were developed in SolidWorks (2015) and meshed by Abaqus (linear tetrahedral mesh, C3D10), and then imported into Preview for further model definition. Both models were evaluated using the FEBio solver.

Model 1:

Model 1 (Figure 1) was based on the anatomy reported (Table 1) with simplified geometries. The acetabulum was assumed to be a cuboid with a hemispherical hole located at the center of the bottom surface to fit the cartilage layer, assumed to be a hemispherical shell. The femoral head was approximated as a sphere while the femoral neck was treated as a cylinder. Specifically, the femoral head was cut with a hemispherical shape fixture at its center. The "female" indentation is located in the top half while the "male" boss is located in the bottom portion.

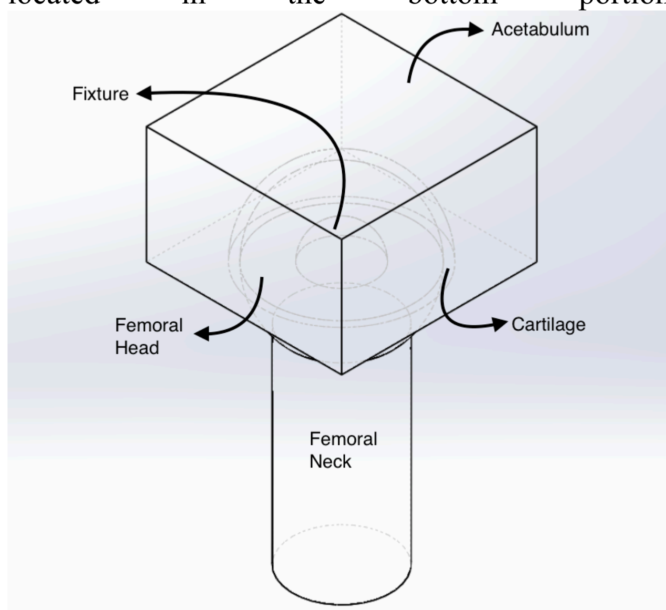

Figure 1: Model 1 geometry

	Dimension [mm]	
Femoral neck	Length [3]	64.30
	Diameter [4]	30.15
Femoral head	Diameter [5]	44.27
Cartilage	Inner Diameter	44.27
	Thickness	2 [6]
Fixture	Diameter	20
Acetabulum	Length/Width	60
	Height	36

Table 1: Dimensions for Model 1

The bone components were described using Neo-Hookean material properties while the cartilage was described as Mooney-Rivlin with the parameters reported in Table 2 [4].

	E	ν	ρ	C_1	C_2	K
Femoral neck [7]	17000	0.28	1800	N/A		
Femoral head [7]	15000	0.3	1800			
Acetabulum [7]	17000	0.3	1800			
Cartilage [7]	N/A		1000	15	1.5	20

Table 2: Material properties for Model 1.

E represents Young's Modulus $[MPa]$; ν represents Poisson's ratio [unitless]; ρ represents density $[^{kg}/_{m^3}]$; K represents Bulk Modulus $[MPa]$; C_1 and C_2 are material parameters for Mooney-Rivlin materials.

Model 1 had approximately 420,000 elements. The sliding interface was defined as the contact surface between the cartilage layer and acetabulum. The femoral head and femoral neck were tied together. The cartilage layer was also tied to the acetabulum. Once material parameters were determined, a uniaxial compressive simulation with a $3000N$ [8] applied at the bottom of the femoral neck was performed to simulate the physiological loading conditions of a walking motion.

<u>Model 2:</u>

Model 1 had several deficiencies. The geometry was simplified and caused stress concentrations at multiple locations. The cartilage layer attached to the acetabulum was missing. Also, the trabecular and cortical bone, which share distinct modulus, were not separated. Therefore, Model 2 was developed to better mimic human anatomy in order to provide more reliable simulation results.

Based on an online open source geometry obtained from a human thighbone CT scan [8], Model 2 was developed. The femoral head, femoral neck and a segment of the femoral stem of the geometry were adapted. Using the *Shell* and *Intersect* functions in SolidWorks (2015), a trabecular bone model and a cortical bone model with a thickness of $1.5mm$ [9] were developed. In addition, an acetabulum part and two layers of cartilage with validated dimensions were also produced. The femoral head was held together with a chamfered cylindrical fixture at the center in accordance with current surgical technique constraints.

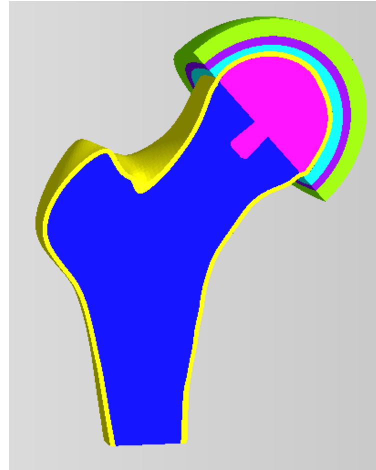

Figure 2: Model 2 geometry with all components

With Model 1, the bone and cartilage components, along with the acetabulum and cartilage layers in Model 2, shared the same material descriptions and material parameters, respectively. Due to the cortical and trabecular bone separation, other materials parameters were correspondingly modified. (Table 3)

	E	ν	ρ
Femoral neck/head (Cortical) [7]	17000	0.28	1800
Femoral neck (Trabecular) [7]	1000	0.3	1000
Femoral head (Trabecular) [7]	600	0.3	1000

Table 3: Material properties for Model 2

Model 2 had approximately 720,000 elements. The sliding interface was defined both at the cartilage-cartilage interface. The trabecular bone was tied to the corresponding cortical bone while the femoral head was tied to the femoral neck. Same as Model 1, the cartilage layers were correspondingly tied to the acetabulum and femoral head. To simulate the same physiological loading conditions as Model 1 while maintaining model stability, the top surface of the acetabulum was fixed while $0.1\,mm$ of prescribed compressive displacement was applied to the bottom surface of the femoral stem. To prevent excessive rotation, the femoral stem bottom surface was constrained so it was only allowed to translate in the displacement direction.

RESULTS

<u>Model 1:</u>

High effective stress generally occurred at the femoral neck-acetabulum cartilage layer interface while the largest effective stress, which was around $5MPa$, occurred at the interface of the fixture and femoral head (Figure 3A). High effective strain occurred at the cartilage layer with a maximum value of 1.76% while strains in the bone components were generally lower than 0.2% (Figure 3B). The model confirmed the feasibility of such surgical techniques.

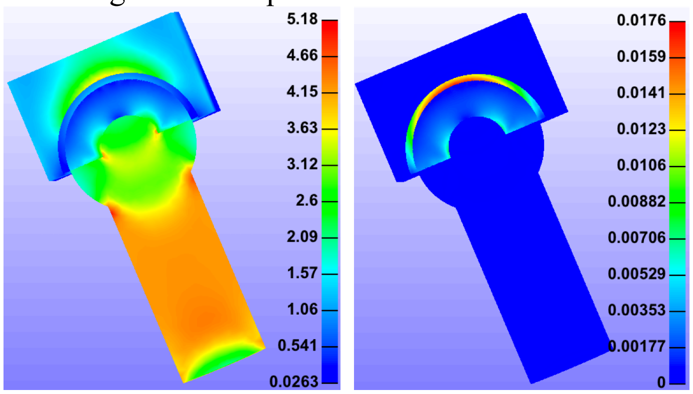

Figure 3: A (left). Effective stress distribution. B (right). Effective strain distribution.

Model 2:

High effective stress was found on the cortical bone of the femoral neck with a maximum value of 1.44 MPa (Figure 4A). High effective strain occurred at the cartilage layer with a maximum value of 0.076% while strains in the bone components were generally lower than 0.008% (Figure 4B).

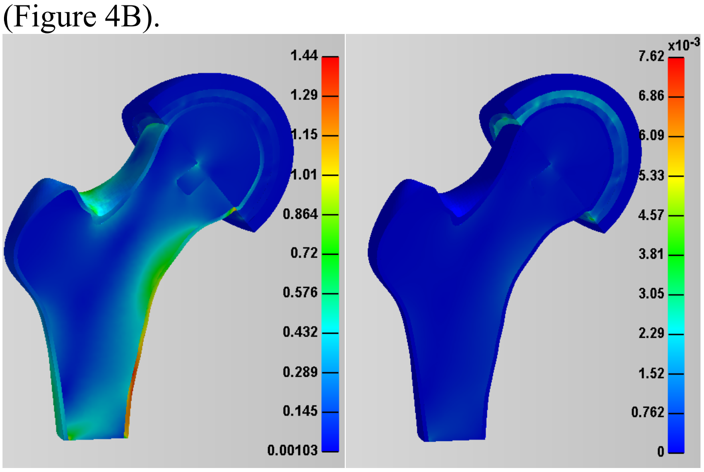

Figure 4: A (left). Effective stress distribution. B (right). Effective strain distribution.

DISCUSSION

In this study, the two models of postoperative hip joints were developed. Some preliminary results regarding the stress states under the loading conditions of walking were obtained. High stress generally occurred in the cortical bone and in the interfaces between adjacent joint parts while high strain was found in the cartilage layers.

This study is still a work in progress. In terms of model development, a graphing technique that helped separate the trabecular and cortical bone was successfully applied. However, a few factors were still not perfectly addressed. All cartilage layers and acetabulum were still developed as spherical shells; compact bone in the femoral neck and the fovea on femoral head were not reflected in Model 2.

In terms of the simulation, the results generated by Model 2 provided a relatively more realistic stress and strain mapping for the postoperative joint. The high stress locations generally had the highest fracture possibility according to case studies of failed THR reported [10]. However, the numerical values presented were not yet reliable due to the current model instability.

In the future, to improve the model, test cases with various fixture geometries will be developed with their results being compared. Specifically, different fixture geometries can significantly affect the stress distribution of the postoperative joint if it is not ideally fused. If the fixture was improperly designed, yielding, fracture or catastrophic failure of the joint could occur. As shown by Model 1 and 2, a properly chamfered fixture could greatly reduce the stress concentration effect and thus increase this surgical technique's successful rate. After obtaining an optimal fixture design, test cases with different loading conditions, including walking, running, and falling, etc. will be developed with their results being compared. Along the study, we will keep communicating with the surgeon about current clinical constraints and requirements to improve the model and help develop more meaningful test cases.

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