Contact sensitivity analysis of FE model of the pelvis with press-fit acetabular prosthesis

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Introduction

Lack of primary stability has been regarded as a major cause for implant loosening in total hip arthroplasty. For a cementless press-fit acetabular cup, primary stability is achieved by inserting an oversized component into an under-reamed acetabulum. Two features that result from the press-fitting process are – 1) pre-stress due to the difference in the radii of the cup and the reamed acetabulum and 2) a gap in the polar region between the dome of the cup and the acetabulum. There are experimental studies that investigate the stability of various contact conditions of press-fit cups such as [1]. However uncertainties still remain as to what effects different contact conditions have on FE simulation results. There exist FE studies that modelled the pelvis and cementless press-fit cups together but frictional contact without press-stress or polar gap is used frequently in such studies [2]. Moreover it is not clear how different contact conditions affect load transfer patterns to the trabecular bone. This study aims to investigate these two problems.

Method

This study is composed of three parts: 1) performing experimental study with a cadaveric pelvis; 2) generating a finite element (FE) model of the same pelvis for comparison with experimental results; 3) investigating how stress transfer is affected by different contact conditions during gait

An embalmed pelvis was harvested and five rosette strain gauges were attached around the acetabulum and the ilium. An uncemented acetabular prosthesis (AML Total Hip System, Depuy) with a 56mm cup was placed, which was positioned in 45˚ abduction and 15˚ anteversion. The acetabulum was reamed within 2mm of the cup size, thus the size of the last reamer was 54mm. Then the pelvis was positioned upside down in a mounting pane with the iliac crest fixed in acrylic cement. An Instron machine (5800 series) was used to direct a vertical force of 600N (Figure 1). Principal strains were measured from the strain gauges.

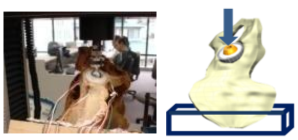
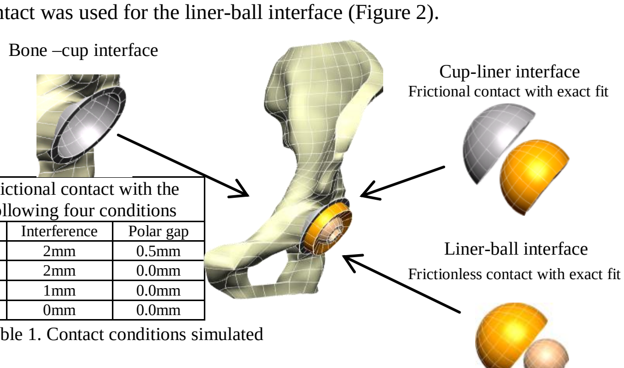


Figure 1: Loading condition for the experiment and FE analysis

The harvested pelvis was CT scanned and a FE model was generated using a previously validated procedure [3]. A synthetic phantom was also scanned, which was used to calibrate CT numbers into densities and then moduli using the method in [4]. The cortical bone was modeled as homogenous and linear elastic material with a modulus of 17GPa [3]. However the thickness of the cortical bone was obtained from CT scans using a previously developed method [3]. The cancellous bone was modeled as heterogeneous material with modulus values obtained from CT scans. FE models of all the components of the press-fit acetabular prosthesis were generated which included a titanium cup, polyethylene liner and CoCr ball. Geometries were obtained from manufacturer's specifications and material properties from the literature.

Four different contact conditions were simulated by changing the amount of overlap between the cup radius and acetabulum radius (called interference) and the gap between the dome of the acetabulum and the cup (called polar gap). Details of the contact conditions are given in Table 1. Three interfaces were modelled in our model – 1) bone-cup interface between the acetabulum and metal cup; 2) cup-liner interface between the metal cup and poly liner; 3) liner-ball interface between the poly liner and CoCr ball. Frictional contact (μ=0.5) was used for the cup-bone and cup-liner interfaces while frictionless contact was used for the liner-ball interface (Figure 2).



Frictional contact with the following four conditions		
	Interference	Polar gap
C1	2mm	0.5mm
C2	2mm	0.0mm
C3	1mm	0.0mm
C4	0mm	0.0mm

Table 1. Contact conditions simulated

Figure 2: Summary of FE simulation contact and interface conditions

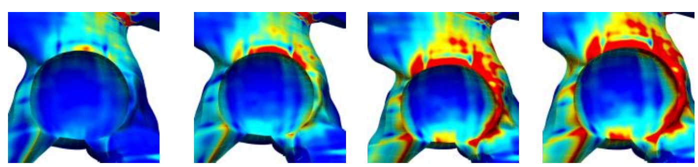
The same loading condition as the experiment was used to calculate surface strains (Figure 1). The results were compared with experimental strains and RMS error was calculated. Gait data from [5] was then used for boundary conditions and normal walking was selected for simulation. The gait cycle was divided into ten steps and the corresponding joint contact forces at the first 50% of the cycle (from heel strike to toe off) were applied to the CoCr ball. Stresses at the trabecular bone were calculated to examine how load transfer to the trabecular bone is affected by different contact conditions.

Results

The contact conditions at the bone-cup interface affected surface strains greatly as shown in Table 2. When compared with experimental strains, the FE model without pre-stress or polar gap had an RMS error of nearly 50%, indicating that having well-defined contact conditions is vital in creating accurate FE models. Pre-stress had a major impact on both surface strains and load transfer pattern. Figure 3 showed a marked change in stress distribution as the amount of pre-stress increased. When there was no pre-stress, the load transfer was minimal as can be seen from Figure 3. Moreover, the effect of polar gap was also seen in the stress plot especially in the inferior part of the acetabulum. The level of stress experienced by the bone in that region was increased as the polar gap decreased (Figure 3).

Contact conditions		**RMS error between the experimental and FE strains**
Interference	**Polar gap**	
2mm	0.5mm	16%
2mm	0.0mm	14%
1mm	0.0mm	29%
0mm	0.0 mm	49%

Table 2. Comparison results between experimental and FE simulated strains



0 mm interference 0 mm polar gap | 1 mm interference 0 mm polar gap | 2 mm interference 0.5 mm polar gap | 2 mm interference 0 mm polar gap

Figure 3. Trabecular von Mises stress under different contact conditions at the 40% of the gait cycle (when the hip joint force is the maximum)

Discussions

This study examined the effects of the contact conditions in the FE model of the pelvis and the cementless press-fit cup. Comparison with the experimental data showed that incorporating both pre-stress and polar gaps is vital in creating an accurate FE model. If perfect contact is assumed without any pre-stress or polar gap, the RMS error could be as high as 50%. Contact conditions were also shown to have a direct bearing on the way load is transferred to the trabecular bone. The von Mises stress plot showed that having adequate pre-stress is vital in achieving good load transfer. Moreover the presence of polar gap also affected the stress transfer especially on the inferior region of the acetabulum. Therefore our results indicate that both pre-stress and polar gaps should be incorporated when modeling the pelvis with press-fit acetabular prosthesis. Recently, Udofia et al. [6] examined the initial stability of a press-fit resurfacing cup. They found that pre-stress due to 1-2 mm interference would be required to avoid excessive micromotion. Our study showed that pre-stress was also important in obtaining accurate surface strains and in achieving good load transfer between the prosthesis and bone. Although it is a result from one pelvis, our study demonstrated the importance of well-defined contact conditions in FE analysis and the role of pre-stress in load transfer between bone and implant.

Reference

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