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Acetabular Component Deformation under Rim Loading using Digital Image Correlation and Finite Element Methods

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Abstract:
Total hip replacement is a highly successful operation; restoring function and reducing pain in arthritis patients. In recent years, thinner resurfacing acetabular cups have been introduced in order to preserve bone stock and reduce the risk of dislocation. However concerns have been raised that deformation of these cups could adversely affect the lubrication regime of the bearing; leading to equatorial and edge contact, possibly causing the implants to jam. This study aims to assess the amount of deformation which occurs due to the tight peripheral fit experienced during press-fit by applying rim loading to three different designs of acetabular cup: a clinically successful cobalt chrome resurfacing cup, a prototype composite resurfacing cup and a clinically successful polyethylene monobloc cup.

Digital Image Correlation (DIC) was used to measure the deformation and to validate Finite Element (FE) models. DIC provided a non-contacting method to measure displacement; meaning the load could be increased continuously rather than in steps as in previous studies.

The physical testing showed that the cobalt chrome cups were significantly stiffer than the composite prototype and polyethylene cups. The FE models were in good agreement with the experimental results for all three cups and were able to predict the deformation to within 10%. FE models were also created to investigate the effect of cup outside diameter and wall thickness on stiffness under rim loading. Increasing outside diameter resulted in a linear reduction in stiffness for all three materials. Increasing the wall thickness resulted in an exponential increase in cup stiffness.

Rim loading an acetabular shell does not accurately simulate the *in vivo* conditions; however it does provide a simple method for comparing cups made of different materials.

Introduction:
In the UK there has been a trend towards more cementless total hip replacement and fewer cemented procedures [1]. For a non-cemented acetabular cup, initial stability is achieved by a press fit between the cup and bone [2, 3]. The acetabulum is reamed to a slightly smaller size than the implant, typically by between 1 and 3mm, the pressure of the bone against the cup provides initial stability [3, 4]. In order to preserve bone stock and reduce the risk of dislocation, thinner resurfacing cups have been introduced [5, 6]. However the use of thinner more flexible cups has raised concerns about the potential for deformation during impaction [5, 6]. Such deformation could adversely affect the fluid film lubrication of metal-on-metal bearings [7], it could also lead to equatorial and edge contact possibly causing the implants to jam [5, 6]. Cup deformation could also influence implant stability and fixation, producing unfavourable conditions for osseointegration and possibly affect periprosthetic bone remodelling [5, 6].

On press fitting of a hemispherical acetabular cup, load transfer occurs predominantly near the rim of the cup and is greatest in the diagonal axis between the Ilium and ischial columns [6, 8] (Figure 1). This study aims to assess the amount of deformation which occurs due to the tight peripheral fit experienced during press-fit by applying rim loading to three different designs of acetabular cup: a clinically successful cobalt chrome resurfacing cup, a prototype composite resurfacing cup and clinically successful polyethylene monobloc cup. Digital image correlation (DIC) was used to measure the deformation and to validate finite element (FE) models. Various studies have used physical testing to validate FE models of implants [9-11] however to the authors' knowledge DIC has not been previously been used in this application.

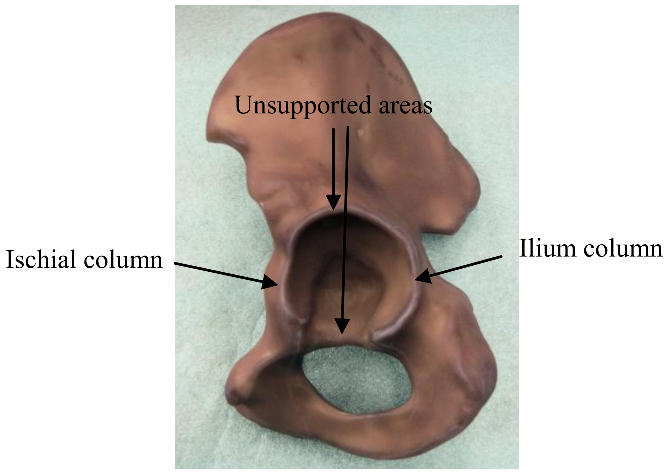

Figure 1 medial view of the pelvis

Methods:

In 3D DIC two cameras record the deformation process of a sample as it is subjected to mechanical forces (figure 2). The sample has a random dot pattern applied to the surface; this is known as a "speckled" pattern. A series of consecutive stereo images are taken throughout the test, which show the deformed speckled patterns relative to the initial pattern. Proprietary image correlation algorithms are used to analyse the digital images to produce a deformation plot [12]. In this study the speckled cups were positioned directly between the platens of a (Losenhausen) servohydraulic test machine; the displacement was controlled by a PC connected to the servohydraulic test machine, at a rate of 5 mm/min. Proprietary software (Limess Messtechnik & Software GmbH, Berlin, Germany) was used to record the camera images and simultaneously record the applied load from the test machine.

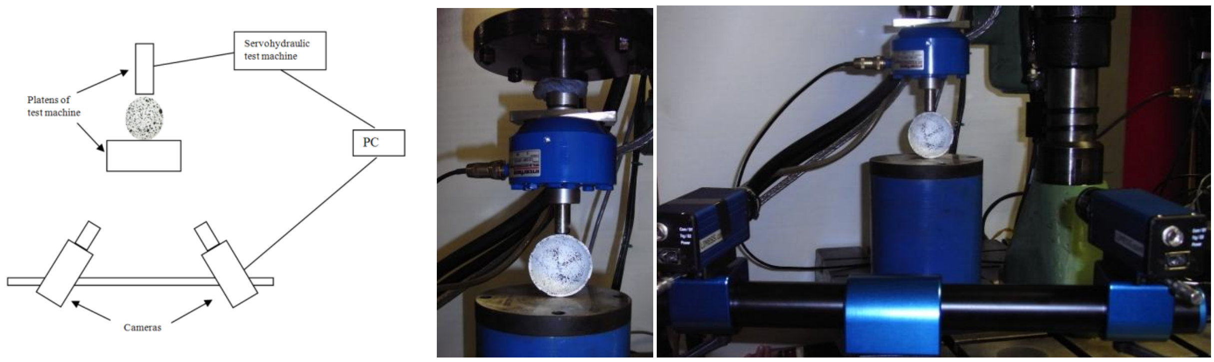

Figure 2 schematic diagram of DIC set up showing test piece, two cameras, PC and servohydralic machine (left), close up photo of speckled cup in test machine (centre), photo of camera and speckled cup (right)

Six different sized CoCr cups were tested (outside diameter 48 to 62mm). At the time of testing only one size of prototype composite cup was available. Due to availability it was not possible to test polyethylene monobloc cups; however 3 sizes of polyethylene liners were used to validate the FE model. A minimum of two cups for each size was tested for each material.

Abaqus CAE version 6.8-1 was used to create finite element models of the cups. The models were meshed using a free meshing technique with a 10 node modified quadratic tetrahedron mesh (Figure 3), the largest cups had around 20,000 elements. The test platens of the test machine were modelled as rigid bodies, a frictionless surface contact was assumed between the cup and the rigid bodies. The load was applied to the upper rigid body in the y-direction and the lower rigid body was fixed in all degrees of freedom. Finite element models were also used to investigate the effect of wall thickness and cup diameter on cup stiffness.

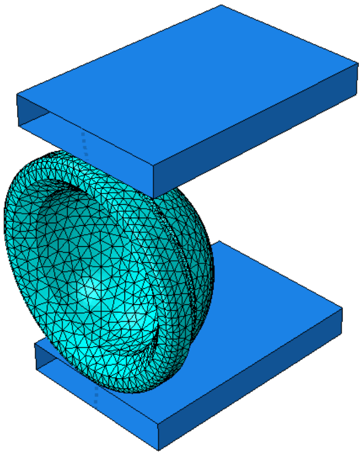

Figure 3 example of a typical mesh (10 node modified quadratic tetrahedron mesh) and rigid bodies

Results:
The track point function of the Vic3D software (Limess Messtechnik & Software GmbH, Berlin, Germany) was used to find the maximum diametric displacement from the digital images. The FE results were plotted as nodal displacement in the y-direction to give the diametric deformation (Table 1&2).

Material	Thickness [mm]	OD [mm]	FE predication (deformation at 300N) [mm]	DIC result (deformation at 300N) [mm]
UHMWPE	11	58	0.49	0.50
UHMWPE	5	42	2.80	2.98
UHMWPE	5	38	2.23	2.31
Composite	3	45	1.78	1.79

Table 1 details of OD and wall thicknesses of polymer cups, maximum diametric deformation FE (3mm mesh density) and DIC results taken at 300N.

Material	Thickness [mm]	OD [mm]	FE predication (deformation at 3000N) [mm]	DIC result (deformation at 3000N) [mm]
CoCr	3	48	0.33	0.36
CoCr	3	50	0.35	0.31
CoCr	3	56	0.42	0.47
CoCr	3	58	0.45	0.47
CoCr	3	60	0.47	0.50
CoCr	3	62	0.49	0.53

Table 2 details of OD and wall thicknesses of CoCr cups, maximum diametric deformation FE (3mm mesh density) and DIC results taken at 3000N.

The Finite Element models were in good agreement with the experimental results for all three materials. Figure 4 shows that refining the mesh size reduced the difference between the experimental DIC results and the FE model. The experimental results showed that increasing the cup size (with constant wall thickness) resulted in a reduction in cup stiffness; confirming that the largest cup size is the worst-case scenario in terms of deflection. As expected the cobalt chrome cups were found to be significantly stiffer than the composite prototype and the polyethylene cup. Figure 5 show the load deflection plot for the three materials tested, the cups shown had an OD of 58mm.

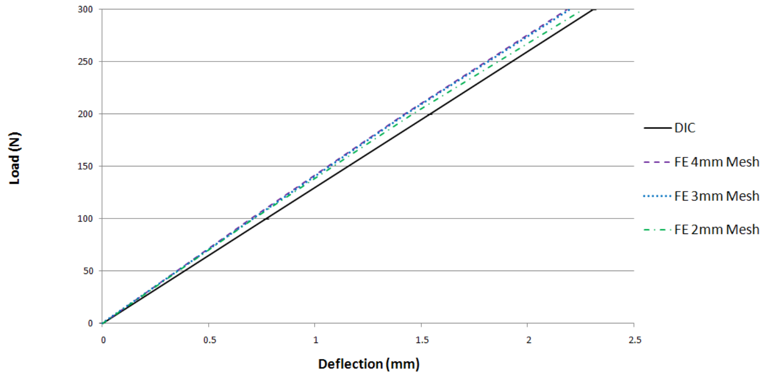

Figure 4 Load deflection plot for a 38mm UHMWPE cup showing DIC and FE results with various mesh sizes

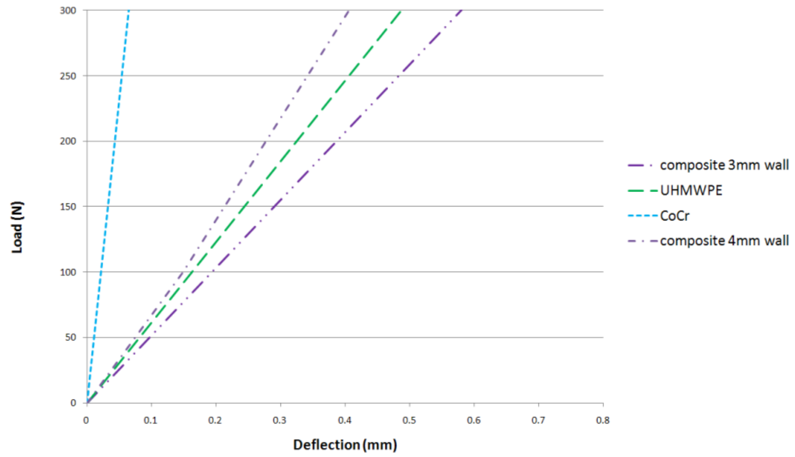

Figure 5 load deflection plot for 58mm cups of various materials

The FE models created to investigate the effect of cup outside diameter and wall thickness on stiffness showed that there was a linear decrease in cup stiffness with increasing outside diameter and an exponential decrease as wall thickness was decreased.

Discussion:

Physical testing has been used previously to validate FE models of implants [9-11, 13]. However to the authors' knowledge this is the first time digital image correlation has been used in this application. Ong et al [13] validated their FE model of acetabular cups using rim loading, cups were deformed under a load of 2kN and the deformation measured using callipers. The model was able to predict the deformations with a 7.1% difference [13]. The FE model in the current study was able to predict the deformation of an acetabular cup under rim loading to within 10%, there was a trend for the FE to overestimate the stiffness of the cups. The CoCr cups were obtained from scrap rather than stock; therefore it is possible they are out of tolerance; meaning that the FE models are not true representations of the actual cups tested. This could explain the variation between FE predictions and DIC results for some of the cups tested.

The load cell used accurate to ±0.5%, the manufacturer of the DIC equipment reports an accuracy of 0.01 pixels, given the 1 mega pixel cameras used this should give an accuracy of 1μm for the 100mm measurement field used. However it has been shown that the properties of the speckled pattern, lighting conditions and measurement system effect the accuracy of the DIC measurement [14]. In the current study the same lighting conditions and measurement equipment was used in all cases, an initial trial run compared two methods of applying the speckled pattern and one was selected based on ease of analysis by the software. These factors may have introduced errors into the experimental measurements. Previous work has shown that the DIC equipment used in this study is accurate to within 5%.

DIC enables continuous measurement of full field displacement throughout testing, without the requirement to contact the sample. Previous studies have used callipers to measure cup deformation [13, 15], which meant that the load had to be applied in a stepwise fashion, and which also introduces the possibility of human error in the measurement. The software also has the advantage of automatically calculating strain values and the option to track the displacement of a defined point. A limitation of the system is access to the field of view required, which may be a problem for physiological loading conditions where a femoral head will be used to apply load.

Rim loading an acetabular shell does not accurately simulate the *in vivo* conditions; however it does provide a simple method for comparing cups made of different materials. A more representative test set up is required to accurately simulate loading of acetabular cups *in vivo,* further work will concentrate on this, in particular testing with cadaveric specimens.

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