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Abstract

Background: Deformation of acetabular cups when press-fitted into an undersized cavity is inevitable due to the inhomogeneous stiffness of acetabular bone. Thinner cups or screw holes might increase the risk of high cup deformation. The aim of this study was to examine the influence of cup design and liner assembly on the deformation response during cup implantation. Methods: Acetabular cups with different designs were implanted into polyurethane foam models simulating the anatomical situation with nominal press-fits of 1mm and without nominal press-fits (line-to-line). Deformations were determined using a tactile coordinate measuring machine. A 3D laser scanner was used to determine the contact conditions at the cup-cavity interface. Polyethylene and ceramic liners were assembled to the implanted cups and the influence of the insertion on the deformation response evaluated. Fixation strength of the cups was determined by push-out testing. Findings: Cup deformation increased with smaller wall thickness ($P<0.037$) and screw holes ($P<0.001$). Insertion of ceramic liners reduced the deformation ($P<0.001$), whereas polyethylene liners adapted to the deformation of the implanted cups ($P>0.999$). Thin-walled cups exhibited a higher fixation strength for similar implantation forces ($P=0.011$). Interpretation: Thin-walled cups achieved higher fixation strengths and might be more bone-preserving. However, in combination with screw holes and high press-fit levels, wall thickness should be considered carefully to avoid excessive cup deformations leading to potential complications during liner assembly. Line-to-line insertion of thin-walled cups should be accompanied with a rough surface coating to minimize the loss of fixation strength due to the low press-fit fixation.

Keywords	hip arthroplasty; press-fit; cup deformation; primary stability; contact condition
Taxonomy	Biomechanical Engineering, Arthroplasty of Hip, Hip Orthopedic Surgery

Corresponding Author	Philipp Messer-Hannemann
Corresponding Author's Institution	TUHH, Hamburg University of Technology, Institute of Biomechanics
Order of Authors	Philipp Messer-Hannemann, Graeme Michael Campbell, Michael Morlock
Suggested reviewers	Matthew Squire, Sophie Williams

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Deformation of Acetabular Press-fit Cups: Influence of Design and Surgical Factors

Philipp Messer-Hannemann, Graeme M Campbell, Michael M Morlock

Institute of Biomechanics, Hamburg University of Technology, Hamburg, Germany

Address correspondence to: Philipp Messer-Hannemann, MSc

Email: philipp.messer@tuhh.de

Hamburg University of Technology, Institute of Biomechanics

Denickestrasse 15, 21073 Hamburg, Germany.

Abstract (249 words)

Main text (3578 words)

Abstract

Background: Deformation of acetabular cups when press-fitted into an undersized cavity is inevitable due to the inhomogeneous stiffness of acetabular bone. Thinner cups or screw holes might increase the risk of high cup deformation. The aim of this study was to examine the influence of cup design and liner assembly on the deformation response during cup implantation.

Methods: Acetabular cups with different designs were implanted into polyurethane foam models simulating the anatomical situation with nominal press-fits of 1mm and without nominal press-fits (line-to-line). Deformations were determined using a tactile coordinate measuring machine. A 3D laser scanner was used to determine the contact conditions at the cup-cavity interface. Polyethylene and ceramic liners were assembled to the implanted cups and the influence of the insertion on the deformation response evaluated. Fixation strength of the cups was determined by push-out testing.

Findings: Cup deformation increased with smaller wall thickness ($P<0.037$) and screw holes ($P<0.001$). Insertion of ceramic liners reduced the deformation ($P<0.001$), whereas polyethylene liners adapted to the deformation of the implanted cups ($P>0.999$). Thin-walled cups exhibited a higher fixation strength for similar implantation forces ($P=0.011$).

Interpretation: Thin-walled cups achieved higher fixation strengths and might be more bone-preserving. However, in combination with screw holes and high press-fit levels, wall thickness should be considered carefully to avoid excessive cup deformations leading to potential complications during liner assembly. Line-to-line insertion of thin-walled cups should be accompanied with a rough surface coating to minimize the loss of fixation strength due to the low press-fit fixation.

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Introduction

The aim of total hip arthroplasty (THA) is to reduce the pain of a diseased hip and to restore the natural joint function. Cementless implantation of acetabular components is a very successful procedure and shows especially for young and active patients with good bone quality promising clinical results (AOANJRR, 2018; Malchau et al., 2015). Since cementless prostheses are implanted by press-fit, deformation of the acetabular cup is inevitable due to the inhomogeneous stiffness of the surrounding acetabular bone (Dold et al., 2016; van Ladesteijn et al., 2018). Choosing the amount of press-fit based on the bone quality (Winter and Karl, 2014) and the shape of the acetabular cavity (García-Rey et al., 2012) is essential to limit cup deformation, while achieving a sufficient implant fixation to prevent early loosening of the implant during loading (Jasty et al., 1997).

The design of the acetabular component is a crucial factor when dealing with the deformation response due to implantation. Previous studies have investigated the influence of cup design, wall thickness and subsequent liner insertion on the shape change of the acetabular component (Goebel et al., 2013; Hothan et al., 2011; Markel et al., 2011; Meding et al., 2013). The relation between cup deformation and initial fixation strength of acetabular cups with different wall thicknesses has not yet been investigated. Thin-walled acetabular cups are advantageous to enable the preservation of bone stock while accommodating larger femoral head sizes for an increased range of motion (Affatato et al., 2007). However, thinning of the acetabular implant increases the risk of a highly deformed cup leading to potential complications during subsequent polyethylene or ceramic liner assembly. In clinical practice the liners provide a low-friction bearing with the articulating femoral head. They are assembled into the implanted cup with multiple hammer blows and fixed by a tapered locking mechanism. A highly deformed cup may enhance the friction between femoral head and inserted polyethylene liner (Schmidig et al., 2010). High wear rates and a possible clamping

of the head inside the liner may result, which increases the risk of a subsequent cup loosening (Ong et al., 2009). An increased deformation of the implanted cup can also cause complications during ceramic liner assembly, leading to possible liner chipping or fracture during loading due to a misalignment of the liner (McAuley et al., 2012; Postak et al., 2009).

With increasing the overall press-fit level at the bone-implant interface also the press-fit close to the equatorial rim of the cavity increases. An increased press-fit close at the equatorial rim of the acetabular cavity results in high radial compressive forces to fixate the cup (Widmer et al., 2002). Transfer of the load through the peripheral cortical bone of the acetabulum is hereby reconstructing the force transmission of the natural hip (Dorr et al., 2000; Small et al., 2013). However, increasing the equatorial press-fit might result in insufficient cup seating, decreasing the bone coverage of the implant, which is important to enable bone ingrowth and to provide a good long-term fixation (Jasty et al., 1997).

The high variability in acetabular shape and bone quality can result in high variations of the mechanical properties during experimental testing (Wähnert et al., 2011). Therefore rigid polyurethane (PU) foam is well-established as bone substitute for analysing the cementless acetabular cup implantation (Antoniades et al., 2013; Fritsche et al., 2008; Macdonald et al., 1999). In particular using a two-point pinching PU foam model replicating the in-vivo loading conditions (Dold et al., 2016; Squire et al., 2006) is widely used to simulate the cementless implantation of acetabular components (Crosnier et al., 2014; Jin et al., 2006; Meding et al., 2013).

The aim of this study was to assess the influence of a decreased cup wall thickness and screw holes on the deformation of the acetabular component as well as on the initial fixation strength after implantation. Furthermore the influence of the subsequent insertion of crosslinked polyethylene (PE) and ceramic (CE) liners on the deformation response was investigated.

Methods

Three different acetabular cup designs with a common outer diameter of 56 mm (Depuy Synthes, Leeds, UK) were implanted into two-point pinching PU foam models of the acetabulum replicating the mechanical support of the anterior and posterior columns (density ρ = 30 pcf; Sawbones Europe AB, Malmö, Sweden) (Jin et al., 2006). Regular multi-hole cups (Regular MH; Figure 1A) with a wall thickness including coating of 3.87 mm (SD 0.03 mm) and thin-walled multi-hole cups (Thin-walled MH) with a similar design and a reduced wall thickness of 2.86 mm (SD 0.04 mm) were implanted and compared to regular single-hole cups without screw holes (Regular SH; Figure 1B).

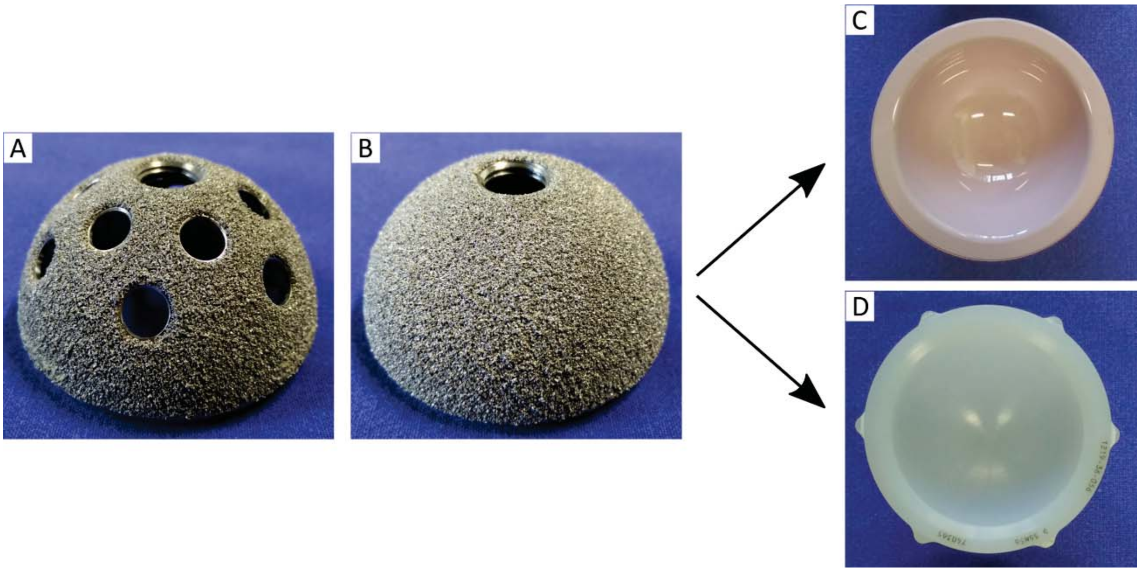

Figure 1: Components used for experimental testing. A: Multi-hole cup; B: Single-hole cup; C: Ceramic liner; D: Polyethylene liner.

The MH cups were implanted with a nominal press-fit of 1 mm and without a defined nominal press-fit (line-to-line), whereas the Regular SH cups were implanted with a line-to-line fit only. The nominal press-fit is defined as difference between the nominal outer cup diameter and the final reamer diameter; for line-to-line implantation the press-fit between implant and surrounding cavity is achieved by the thickness of the surface coating only, which is not considered for the nominal cup diameter. Ceramic (CE) liners (Biolox delta 36/56, CeramTec GmbH, Plochingen, Germany; Figure 1C) and crosslinked polyethylene

(PE) liners (Marathon 36/56, DePuy Synthes; Figure 1D) were inserted into the Regular SH cups to analyse their influence on the deformation response. The single-hole cup design was used to assess the liner deformation since the liners didn't fit into the thin-walled cups due to a different taper geometry. Furthermore, the comparison of the multi-hole cups was focused on the influence of an altered wall thickness on the initial fixation strength; the seating of the multi-hole cups could have been altered by the subsequent liner insertion, which therefore was omitted. The metal cups had a highly porous surface coating and each combination of cup design, press-fit level and additional liner assembly was tested three times (n = 3) using unused foam blocks (Table 1).

Table 1: Study design for the experimental testing. Each combination of cup design, press-fit level and additional liner assembly was tested three times.

Cup design	Nominal press-fit	Liner	n
Thin-walled MH	1 mm	-	3
	Line-to-line	-	3
Regular MH	1 mm	-	3
	Line-to-line	-	3
Regular SH	Line-to-line	Polyethylene	3
		Ceramic	3

Prior to testing, the geometry of all components was determined using a tactile coordinate measuring machine (CMM) (Crysta Apex S, Mitutoyo, Kawasaki, Japan) with an accuracy of 2.2 µm to confirm the initial pristine condition, in particular the undeformed shape of the metal cup. Foam block cavities were manufactured with diameters $Ø_C$ of 55 mm and 56 mm to ensure the nominal press-fit levels. A cylindrical section with a height of 2 mm directly below the entrance plane of the foam block was generated by locating the center of the spherical cavity 2 mm below the entrance plane (Figure 2). The cups were implanted quasi-statically (v = 0.1 mm/s; Model Z010, Zwick GmbH & CoKG, Ulm, Germany) until the coating of the cup was flush with the top entrance plane of the foam block, ensuring that the

cup did not bottom-out before peripheral fixation occurred (Figure 2). As a consequence a polar gap between the dome of the implanted cup and the bottom of the cavity remained.

The cup deformation was determined in a depth of 6 mm from the cup entrance plane at the inner cup taper using the CMM and a ruby stylus (Ø 2 mm). The deformation was measured at the inner cup taper, since a deformation in this area directly influences the locking mechanism of the subsequently assembled liner. The liner deformation was determined in the same depth in order to compare the measurements. Component deformation was defined as difference between the diameter of the maximum inscribed (d_{min}) and minimum circumscribed circle (d_{max}) fitted to the measured point cloud (MATLAB R2016b, Mathworks, Natick, Massachusetts, USA; Figure 3B).

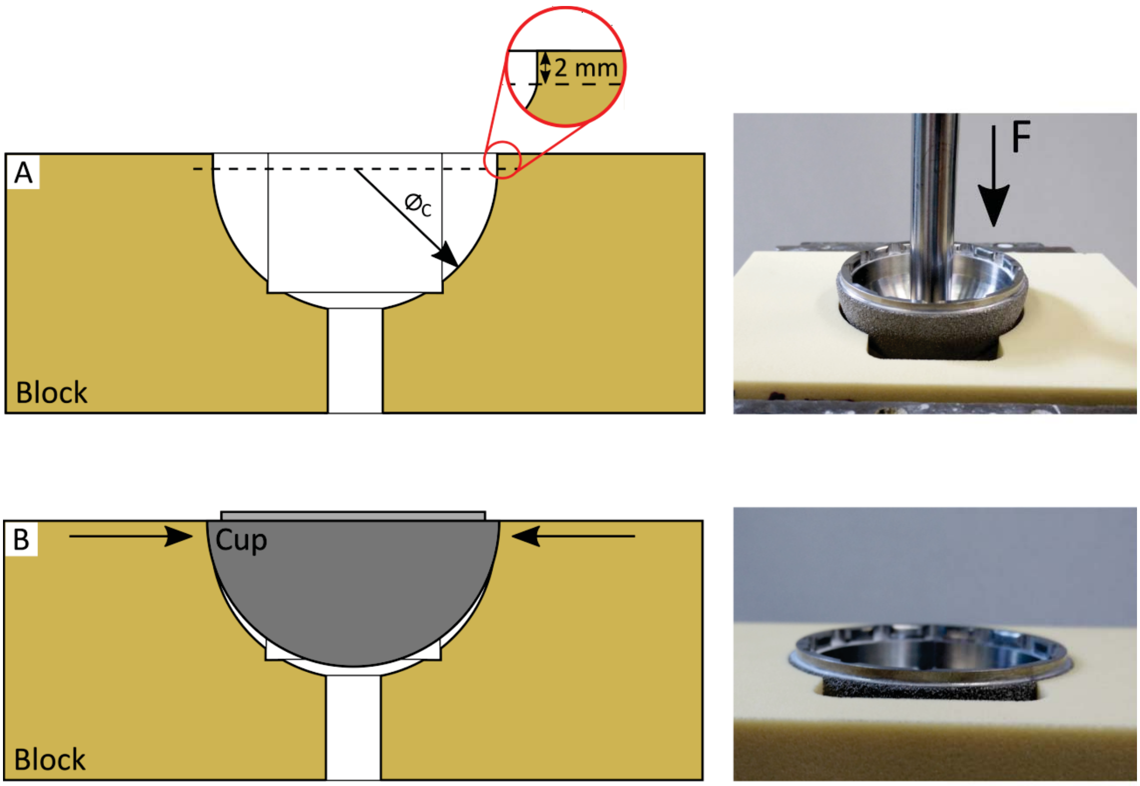

Figure 2: Implantation of the cementless press-fit cups. A: The shape of the cavity with a 2 mm cylindrical section below the entrance plane ensured peripheral fixation of the cup (B). Arrows indicate the location of the radial compressive forces due to the press-fit.

The subsequent liner insertion into the Regular SH cups was performed quasi-statically and displacement-controlled until a maximum force of 1000 N was reached. Pilot testing did show that this force ensured a sufficient seating of the liner without further seating of the implanted cup. In the tests with additional liner assembly, the PE liner was inserted first and the liner deformation assessed. This was followed by a push-out of the PE liner. Subsequently the CE liner was inserted into the same cup and the process repeated. The deformation of the inserted liners as well as of the cup before and after liner assembly were measured with the CMM. New PE and CE liners were used for each test.

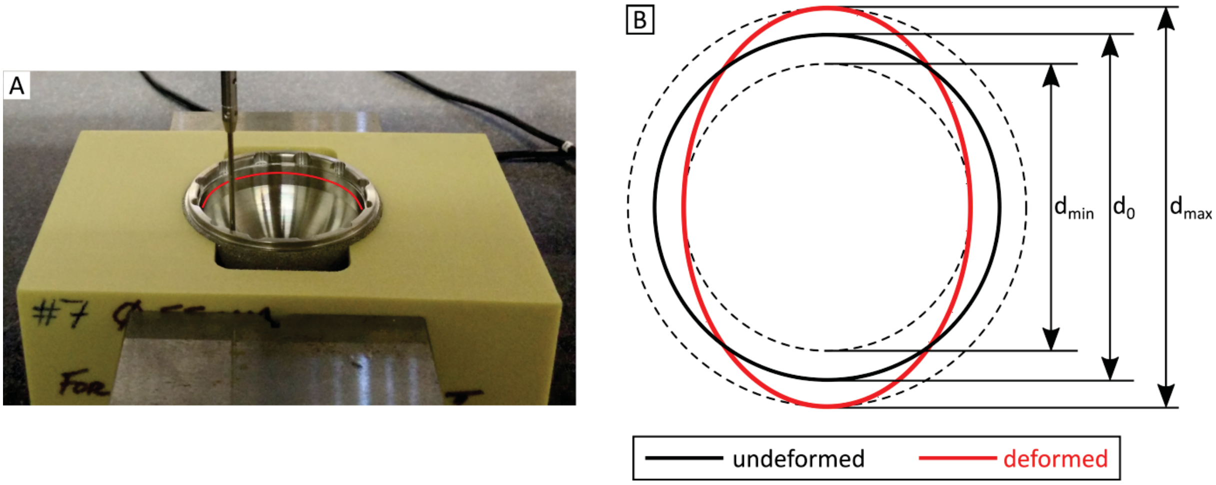

Figure 3: A: The cup deformation was measured in a depth of 6 mm from the cup entrance plane using a tactile coordinate measuring machine (the measuring path is indicated in red). B: The component deformation is defined as the difference between the diameter of the maximum inscribed (d_{min}) and minimum circumscribed circle (d_{max}).

The contact condition at the interface between cup and cavity was visualized using a hand-guided 3D laser scanner (HandySCAN 700, Creaform, Québec, Canada) with a spatial resolution of 200 µm and an accuracy of 30 µm. The cup and the foam block were scanned separately prior to implantation. These scans were then rigidly registered to the post-implantation scan using a least-square algorithm (VXmodel, Creaform, Québec, Canada), such determining the position of the cup inside the cavity (Figure 4). Then the closest-point distance between the outer cup surface and the inner surface of the cavity was used to

determine the contact conditions at the cup-cavity interface after implantation. The effective press-fit was determined by comparing the outer cup diameter, which was determined as the mean distance of the coating asperities to the origin of a sphere fitted to the scanned outer cup surface, with the diameter of the cavity.

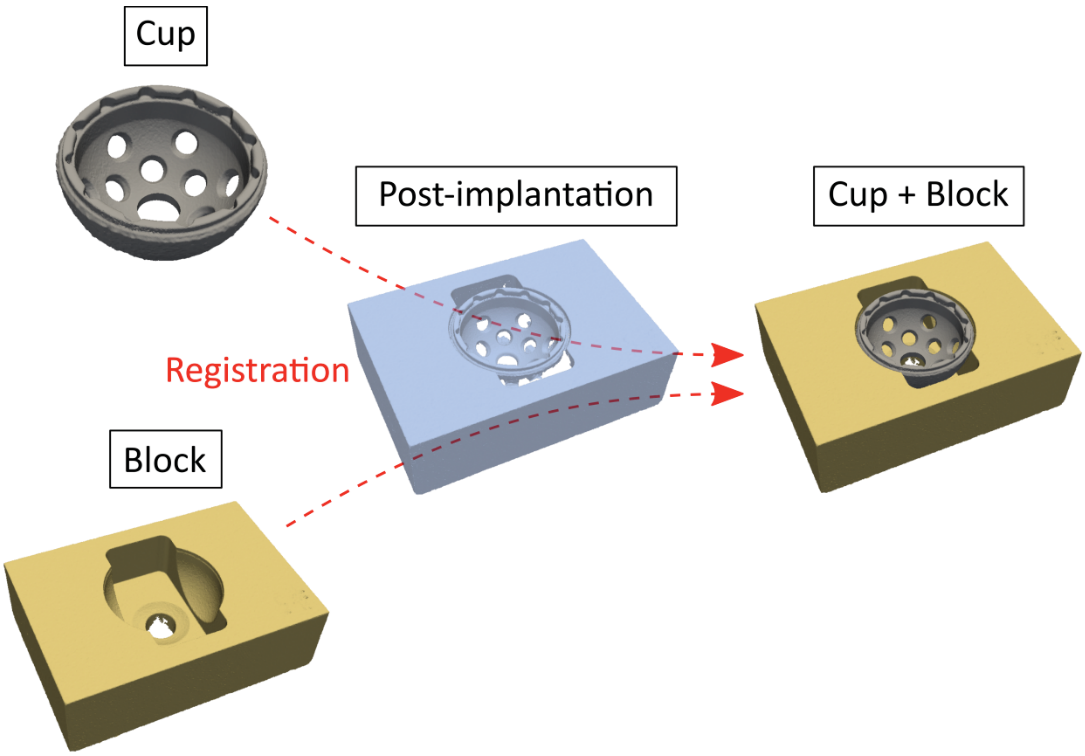

Figure 4: Separate 3D models of the cup and the PU foam block were generated and rigidly registered to the post-implantation scan in order to analyse the local press-fit distribution at the cup-cavity interface.

Metal pins with different diameters were used for the push-out of the components through the hole at the back of the foam block to determine the initial fixation strength (v = 0.1 m/s; Figure 5). To avoid a bending of the foam block during cup push-out and to prevent movement of the cup during liner push-out, a metal plate was used to support the block and the cup, respectively. The influence of the cup wall thickness on the initial fixation of the implanted cup was analysed by calculating the ratio of the push-out force and the press-in force (POPI, push-out/press-in) in order to compensate the individual test conditions.

Statistical analysis was performed using SPSS 24.0 (SPSS Inc., Chicago, IL, USA). All relevant variables were tested for normality (Shapiro-Wilk test) and homogeneity of variances (Levene's test) to check for parametric testing. Pearson's correlation, independent t-tests and ANOVA with Tukey HSD tests for pairwise comparison were used to study associations between parameters and differences between groups. A type I error level of 0.05 was used for all tests of significance.

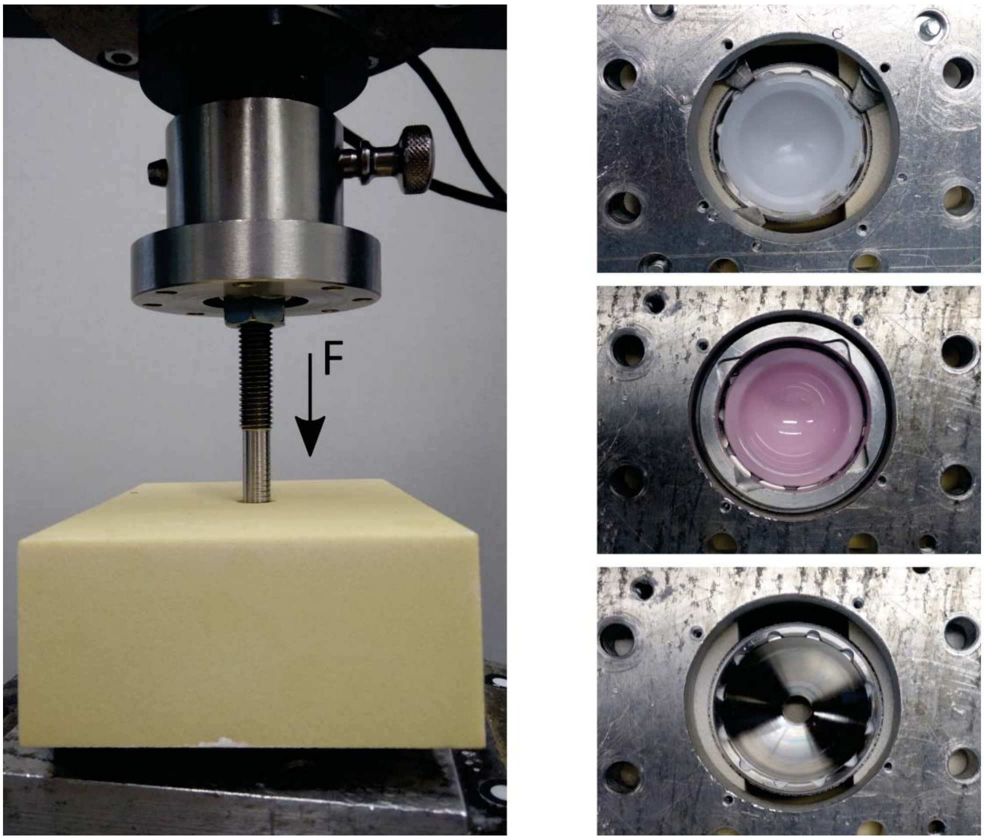

Figure 5: Left: Setup to determine the initial fixation strength. Right: Push-out of the PE liner, the CE liner and the cup through the hole at the back of the foam block using metal pins with different diameters. A metal plate was placed on the PU-block to avoid movement of the cup during liner push-out and bending of the block.

Results

The effective press-fit was about 0.20 mm higher than the nominal press-fit for both press-fit levels (Table 2). No significant differences of the effective press-fits between the different

cup designs were observed at either press-fit level (*P* = 0.639). The Thin-walled MH cups deformed more during implantation than the Regular MH cups, for both press-fit levels (line-to-line: *P* = 0.037; 1 mm press-fit: *P* = 0.023; Figure 6). The Regular SH cups without screw holes deformed less during line-to-line insertion than the Regular MH cups with screw holes (*P* < 0.001; Figure 6).

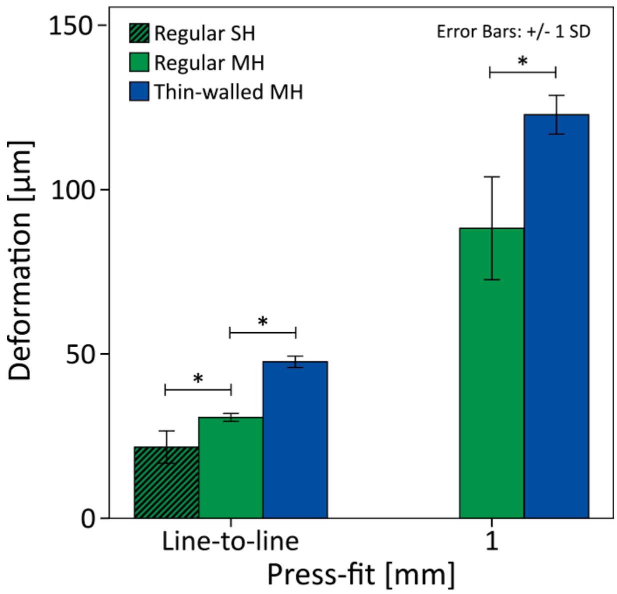

Figure 6: Cup deformations of the three cup designs due to implantation into physiological PU foam blocks simulating the anatomical situation.

Table 2: Cavity diameters, outer cup diameters and effective press-fits for the different cup designs (mean and standard deviation).

Nominal press-fit	**Cup design**	**Ø$_{C}$ [mm]**	**Ø$_{Cup}$ [mm]**	**Effective press-fit [mm]**
1 mm	Thin-walled MH	55.03 (SD 0.02)	56.28 (SD 0.05)	1.22 (SD 0.06)
	Regular MH	55.03 (SD 0.01)	56.23 (SD 0.06)	1.20 (SD 0.01)
Line-to-line	Thin-walled MH	56.02 (SD 0.02)	56.26 (SD 0.09)	0.20 (SD 0.08)
	Regular MH	56.04 (SD 0.02)	56.23 (SD 0.01)	0.19 (SD 0.03)
	Regular SH	56.05 (SD 0.01)	56.22 (SD 0.10)	0.17 (SD 0.10)

The local distribution of the press-fit areas showed for both press-fit levels the intended gap between the dome of the cup and the bottom of the cavity after implantation (Figure 7). The

radial compressive forces acting on the cup for a nominal press-fit of 1 mm were distributed around the periphery of the cavity in the areas of contact. For a line-to-line implantation only the highest asperities of the cup coating were in contact with the cavity, which reflected in reduced push-out forces ($P < 0.001$; Table 3).

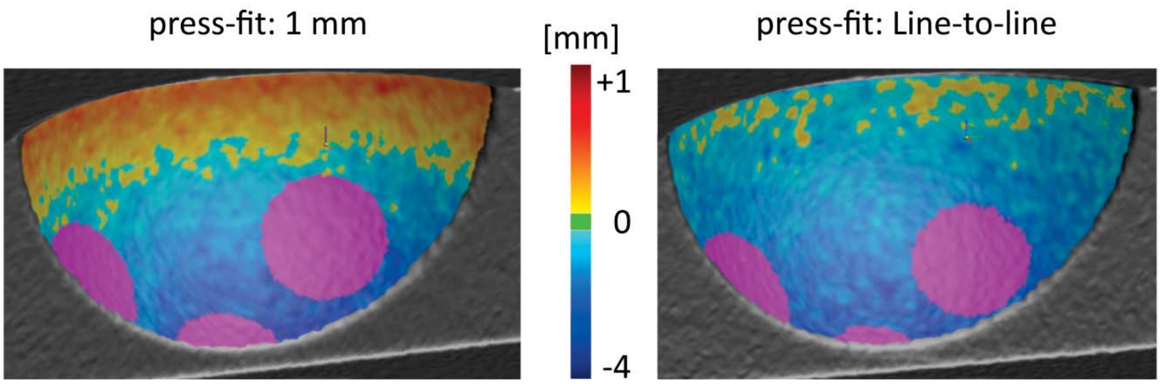

Figure 6: Press-fit distribution at the interface between cup and PU foam cavities in the contact regions for both press-fit conditions. Positive values (red and yellow) indicate an interference of the two surfaces ("press-fit"). Pink areas indicate missing surface data.

Table 3: Press-in and push-out forces as well as the cup deformations after implantation for the different cup types and press-fit levels (mean and standard deviation).

Nominal press-fit	**Cup design**	**Press-in [N]**	**Push-out [N]**	**Deformation [µm]**
1 mm	Thin-walled MH	6113 (SD 189)	1111 (SD 26)	123 (SD 6)
	Regular MH	5373 (SD 250)	851 (SD 170)	88 (SD 16)
Line-to-line	Thin-walled MH	1728 (SD 176)	342 (SD 103)	48 (SD 2)
	Regular MH	1747 (SD 37)	287 (SD 20)	31 (SD 1)
	Regular SH	1626 (SD 377)	184 (SD 58)	22 (SD 5)

Fixation strength of the MH cups increased with cup deformation independent of the cup wall thickness ($R^2 = 0.953$, $P < 0.001$; Figure 8A). The POPI-index was clearly higher for the Thin-walled MH cups compared to the Regular MH cups ($P = 0.011$; Figure 8B). This indicates that a lower implantation force needed to ensure similar fixation strength with a thin-walled cup.

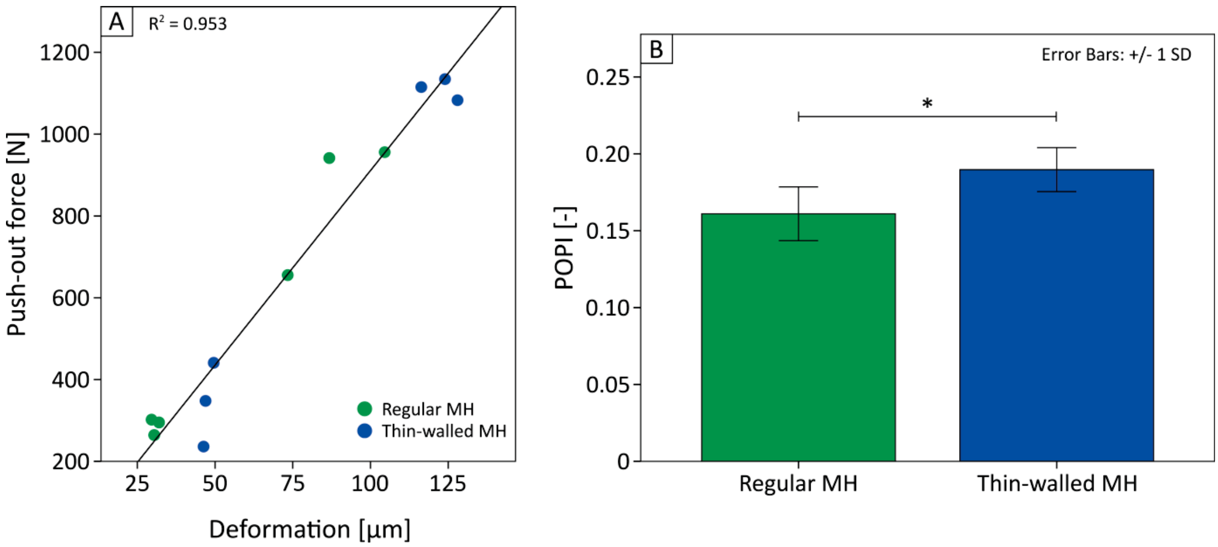

Figure 8: A: Fixation strength of the MH cups increased with cup deformation ($R^2 = 0.953$, $P < 0.001$). B: The POPI-index was higher for the Thin-walled MH cups compared to the Regular MH cups ($P = 0.011$).

Insertion of a PE liner into a Regular SH cup caused the PE-liner to adapt to the deformation of the implanted cup ($P > 0.999$; Figure 9; B vs. C), whereas the insertion of a CE liner reduced the deformation to 2 µm (SD 1 µm) ($P < 0.001$; Figure 9; D vs. E). Cup deformation after push-out of the CE liner was similar to the deformation before insertion of the CE liner ($P > 0.999$; Figure 9; D vs. F). Cup shape after final cup push-out was also similar to the shape before implantation, indicating a purely elastic deformation of the cups due to implantation ($P > 0.999$; Figure 9; A vs. G). Cup deformation after push-out of the PE liner was slightly reduced compared to the cup deformation before PE liner assembly ($P = 0.133$; Figure 9; B vs. D)

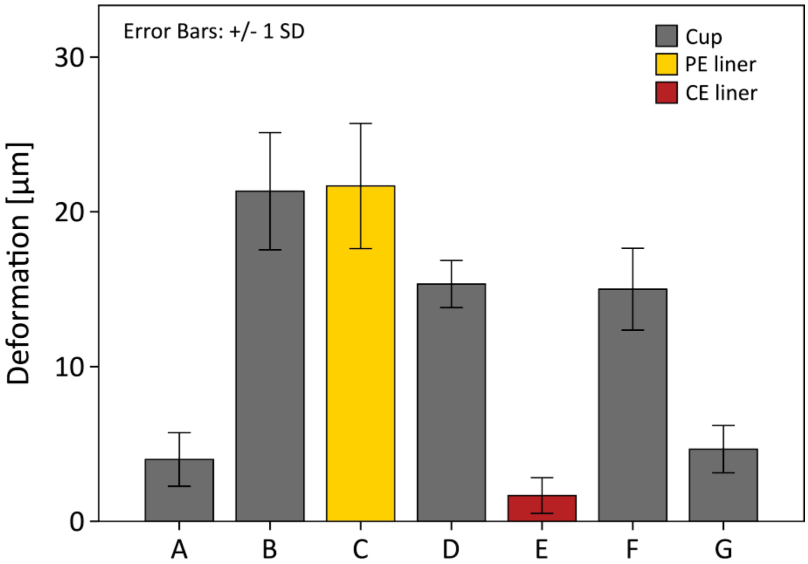

Figure 9: Deformation response of the Regular SH cups implanted with a line-to-line fit. A: cup before implantation; B: cup after implantation; C: PE liner after assembly; D: cup after PE liner push-out; E: CE liner after assembly; F: cup after CE liner push-out; G: cup after push-out.

Discussion

Deformation of the acetabular cup during press-fitting into an undersized cavity is inevitable due to the inhomogeneous stiffness of the acetabular bone around the peripheral rim. A reduction in cup wall thickness of the same cup design is associated with a decreased stiffness of the acetabular cup (Dold et al., 2016), such increasing the magnitude of cup deformation due to implantation. The reduction in cup wall thickness of the investigated multi-hole cup design caused a deformation increase of about 35 µm (40 %) after cup implantation with a nominal press-fit of 1 mm and about 17µm (55 %) for the line-to-line implantation. The decreased cup wall thickness is beneficial to preserve bone stock with the same liner geometry or has the potential to accommodate larger femoral heads with the same outer cup diameter at the cost of higher cup deformation at a given press-fit level. Inserting a polyethylene liner into a deformed cup caused the liner to adapt to the cup deformation, resulting in a reduction of the clearance between the femoral head and the liner. This might be associated with an increased risk of femoral head clamping inside the liner and an altered fluid-film lubrication of the bearing (Goebel et al., 2013; Ong et al., 2009; Schmidig et al., 2010). Polyethylene liners with an increased wall thickness would counteract their adaptation to the cup deformation during insertion, but prevent the potential use of a larger femoral head, which was the idea for decreasing the wall thickness in the first place (Goebel et al., 2013).

The insertion of a stiff ceramic liner reduced the cup deformation to values measured for the undeformed cup prior to implantation. Increasing the stresses in the surrounding bone by the ”expansion” of the metal cup due to the insertion of a ceramic liner into the deformed metal cup could lead to a better implant fixation, but also may increase the periprosthetic fracture risk. Especially for thin-walled cups in combination with a high press-fit level caution should be exercised when inserting ceramic liners, since a highly deformed cup increases the risk of a misaligned liner, liner chipping and potential ceramic liner fractures during loading

(Langdown et al., 2007; McAuley et al., 2012). Consequently, excessive press-fit levels should be avoided when combining thin-walled cups with ceramic liners. In clinical practice the viscoelasticity of the surrounding bone can help to reduce cup deformation if the surgeon waits until the bone relaxation has taken place before inserting a ceramic liner. This would help to reduce the mentioned risks (Manning et al., 2018). Another aspect is the force magnitude required to achieve sufficient seating of the ceramic liner, which may increase with larger cup deformation. High forces to insert the liner could lead to further seating the acetabular cup, which increases the risk of bottoming-out of the cup in the bone cavity with a change in the load transfer between the cup and the bone. Finally, surgical time is precious and waiting – especially over longer periods in time - is not really a feasible option. As a consequence the amount of press-fit should be carefully limited.

Line-to-line insertion of the thin-walled cup decreased the cup deformation but also lowered the initial fixation strength of the implant. Line-to-line insertion should always be combined with a rough surface coating and a high coefficient of friction at the interface between cup and bone in order to minimize this reduction as it is the case in the design investigated. The term "line-to-line" is confusing since it implies that no press-fit is intended. However, this depends solely on the "true" size of the cup in comparison to the nominal diameter given by the manufacturer. For the designs tested, the cup diameter was larger than the nominal diameter due to the surface coating thickness, which results in an effective press-fit. This might be different for other cup designs. From a technical point of view, a cup with a circumferential unequal wall thickness to account for the inhomogeneous bone quality around the acetabulum could be beneficial in order to limit the deformation of the cup without jeopardizing the initial fixation strength. In clinical practice this would, however, introduce a new rotational degree of freedom, which complicates the process of cup positioning and might increase the error susceptibility for the surgeon.

Cup deformation due to implantation correlated with the initial cup fixation strength. This is indicative of the radial compressive forces acting on the cup when press-fitted into the cavity. With the same nominal press-fit level, thin-walled cups exhibit the potential to increase the initial fixation assuming similar implantation forces or to decrease the implantation force in order to ensure similar initial fixation strength compared to cups with a regular wall thickness and a similar cup design. Decreased implantation forces are associated with a reduced risk of tissue damage and could also help the surgeon to align the acetabular component more accurately, which is crucial for a good long-term success (Kennedy et al., 1998).

Additional cups with screw holes were shown to be associated with a reduced stiffness of the cup due to a loss of material compared to the same cup design without screw holes. Multi-hole cups should preferably be used in patients with poor bone quality, where sufficient cup fixation solely by press-fitting is critical, making the use of screws a necessity. Additional screw fixation might not be beneficial in terms of the longevity of the implant for patients with good bone quality (Iorio et al., 2010; Otten et al., 2016). Screws could also pull the implanted cup along the screw axis during screw fixation, which might change the load transfer to the bone and might even generate an equatorial gap at the peripheral rim between cup and bone (Spears et al., 2001). Furthermore, increasing the number of screws might further alter the stress levels in the surrounding bone in comparison to a pure press-fit situation and such influence long-term bone ingrowth or stress shielding.

A higher press-fit level caused an increase in equatorial press-fit area between the cup and the acetabular cavity. This resulted in an increase in the initial fixation strength. However, concentrating the contact close to the equatorial rim is associated with a polar gap between the cup and the bottom of the cavity, which can prevent sufficient bone ingrowth, if the gap is too large. This again should be viewed as an indication to avoid excessive press-fit levels.

There are several limitations to this study. The magnitude of the deformations within this study corresponds to reported in-situ cup deformations supporting the use of a modified PU

foam block as a suitable model to simulate the in-vivo two-point pinching (Dold et al., 2016; Jin et al., 2006; Squire et al., 2006). However, PU foam is homogeneous and does not represent the viscoelastic properties and heterogeneity of bone, which may promote an asymmetric deformation pattern and influences the shape recovery of the acetabular cup over time (Manning et al., 2018). In addition, elastic deformation of the implanted cup was only assessed by performing one line scan with the CMM and according to this; conclusions about the deformation of the entire cup can't be made. The accuracy of around 2 µm of the tactile coordinate measuring machine to determine the cup deformation is deemed appropriate to quantify the shape change of the implanted cup. The resolution of the 3D laser scanner used to visualize the local press-fit distribution (200 µm) was not sufficient to generate a detailed model of the surface coating of the cup. Nevertheless it was sufficient to calculate the outer diameter of the used cups and to qualitatively analyse the contact conditions at the interface. All components of the presented study were inserted quasi-statically, which neglects the dynamic seating behaviour of the implants during surgery. Furthermore, cup deformation after push-out of the PE liner was lower compared to the deformation before liner insertion. This could be due to a slight movement of the cup during liner push-out despite the measures taken. This might have simplified the insertion of the CE-liner. It, however, should not have influenced the comparison between the other conditions. The deformation response observed is specific for the cup sizes and designs investigated. Cup deformation might increase with cup diameter; the quantitative findings should therefore not be expanded to cups with greatly different sizes (Hothi et al., 2014). The qualitative results should be applicable to other cup designs.

Conclusion

The press-fit level as well as the stiffness of the cup design determines the cup deformation due to implantation. Thin-walled cups achieved higher initial fixation strengths and might be

advantageous in terms of bone stock preservation and the use of larger head sizes. The combination with screw holes or higher press-fit levels should be considered carefully to avoid an excessive cup deformation leading to potential complications during liner assembly or clamping of the head. Line-to-line insertion of thin-walled cups should be accompanied with a rough surface coating in order to minimize the loss of initial fixation strength due to a low press-fit fixation, as it is done in the designs investigated.

Acknowledgements

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Conflict of interest

Michael Morlock is a consultant to DePuy Synthes and serves on speaker bureaus for B Braun Aesculap, AORecon, Ceramtec, Corin, Lima, Mathys, Peter Brehm, DePuy Synthes, Zimmer-Biomet. No other authors have conflicts.

References

Affatato, S., Leardini, W., Jedenmalm, A., Ruggeri, O., Toni, A., 2007. Larger diameter bearings reduce wear in metal-on-metal hip implants. Clin. Orthop. Relat. Res. 153–158. https://doi.org/10.1097/01.blo.0000246561.73338.68

Antoniades, G., Smith, E.J., Deakin, a H., Wearing, S.C., 2013. Primary stability of two uncemented acetabular components of different geometry : hemispherical or peripherally enhanced ? Bone Jt. Res. 2, 264–269.

AOANJRR, 2018. Australian Orthopaedic Association National Joint Replacement Registry. Hip, Knee & Shoulder Arthroplasty: 2018 Annual Report. Adelaide.

Crosnier, E.A., Keogh, P.S., Miles, A.W., 2014. A novel method to assess primary stability of press-fit acetabular cups. Proc. Inst. Mech. Eng. H. 228, 1126–34.

https://doi.org/10.1177/0954411914557714

Dold, P., Pandorf, T., Flohr, M., Preuss, R., Bone, M.C., Joyce, T.J., Holland, J., Deehan, D., 2016. Acetabular shell deformation as a function of shell stiffness and bone strength. Proc. Inst. Mech. Eng. Part H J. Eng. Med. 230, 259–264. https://doi.org/10.1177/0954411916632792

Dorr, L.D., Bechtol, C.O., Watkins, R.G., Wan, Z., 2000. Radiographic Anatomic Structure of the Arthritic Acetabulum and its Influence on Total Hip Arthroplasty. J. Arthroplasty 15, 890–900. https://doi.org/10.1054/arth.2000.8323

Fritsche, A., Bialek, K., Mittelmeier, W., Simnacher, M., Fethke, K., Wree, A., Bader, R., 2008. Experimental investigations of the insertion and deformation behavior of press-fit and threaded acetabular cups for total hip replacement. J. Orthop. Sci. 13, 240–247. https://doi.org/10.1007/s00776-008-1212-z

García-Rey, E., García-Cimbrelo, E., Cruz-Pardos, A., 2012. Cup press fit in uncemented THA depends on sex, acetabular shape, and surgical technique. Clin. Orthop. Relat. Res. 470, 3014–3023. https://doi.org/10.1007/s11999-012-2381-9

Goebel, P., Kluess, D., Wieding, J., Souffrant, R., Heyer, H., Sander, M., Bader, R., 2013. The influence of head diameter and wall thickness on deformations of metallic acetabular press-fit cups and UHMWPE liners: A finite element analysis. J. Orthop. Sci. 18, 264–270. https://doi.org/10.1007/s00776-012-0340-7

Hothan, A., Huber, G., Weiss, C., Hoffmann, N., Morlock, M., 2011. Deformation characteristics and eigenfrequencies of press-fit acetabular cups. Clin. Biomech. 26, 46–51. https://doi.org/10.1016/j.clinbiomech.2010.08.015

Hothi, H.S., Busfield, J.J.C., Shelton, J.C., 2014. Deformation of uncemented metal acetabular cups following impaction : experimental and finite element study. Comput. Methods Biomech. Biomed. Engin. 17, 1261–1274. https://doi.org/10.1080/10255842.2012.744397

Iorio, R., Puskas, B., Healy, W.L., Tilzey, J.F., Specht, L.M., Thompson, M.S., 2010. Cementless Acetabular Fixation With and Without Screws. Analysis of Stability and Migration. J. Arthroplasty 25, 309–313. https://doi.org/10.1016/j.arth.2009.01.023

Jasty, M., Bragdon, C., Burke, D., O'Connor, D., Lowenstein, J., Harris, W.H., 1997. In Vivo Skeletal Responses to Porous-Surfaced Implants Subjected to Small Induced Motions. J. Bone Jt. Surg. 79, 707–714.

Jin, Z.M., Meakins, S., Morlock, M.M., Parsons, P., Hardaker, C., Flett, M., Isaac, G., 2006. Deformation of press-fitted metallic resurfacing cups. Part 1: experimental simulation. Proc. Inst. Mech. Eng. Part H J. Eng. Med. 220, 299–309. https://doi.org/10.1243/095441105X69150

Kennedy, J.G., Rogers, W.B., Soffe, K.E., Sullivan, R.J., Griffen, D.G., Sheehan, L.J., 1998. Effect of acetabular component orientation on recurrent dislocation, pelvic osteolysis, polyethylene wear, and component migration. J. Arthroplasty 13, 530–534. https://doi.org/10.1016/S0883-5403(98)90052-3

Langdown, A.J., Pickard, R.J., Hobbs, C.M., Clarke, H.J., Dalton, D.J.N., Grover, M.L., 2007. Incomplete seating of the liner with the Trident acetabular system: A cause for concern? J. Bone Jt. Surg. Br. 89–B, 291–295. https://doi.org/10.1302/0301-620X.89B3.18473

Macdonald, W., Carlsson, L. V., Charnley, G.J., Jacobsson, C.M., Johansson, C.B., 1999. Inaccuracy of acetabular reaming under surgical conditions. J. Arthroplasty 14, 730–737. https://doi.org/10.1016/S0883-5403(99)90229-2

Malchau, H., Graves, S.E., Porter, M., Harris, W.H., Troelsen, A., 2015. The next critical role of orthopedic registries. Acta Orthop. 86, 3–4. https://doi.org/10.3109/17453674.2014.1002184

Manning, W.A., Pandorf, T., Deehan, D.J., Holland, J., 2018. Early shape change behaviour of an uncemented contemporary hip cup: A cadaveric experiment replicating host bone

behaviour through temperature control. Proc. Inst. Mech. Eng. Part H J. Eng. Med. 232, 843–849. https://doi.org/10.1177/0954411918790776

Markel, D., Day, J., Siskey, R., Liepins, I., Kurtz, S., Ong, K., 2011. Deformation of metal-backed acetabular components and the impact of liner thickness in a cadaveric model. Int. Orthop. 35, 1131–1137. https://doi.org/10.1007/s00264-010-1077-6

McAuley, J.P., Dennis, D.A., Grostefon, J., Hamilton, W.G., 2012. Factors affecting modular acetabular ceramic liner insertion: A biomechanical analysis. Clin. Orthop. Relat. Res. 470, 402–409. https://doi.org/10.1007/s11999-011-2193-3

Meding, J.B., Small, S.R., Jones, M.E., Berend, M.E., Ritter, M.A., 2013. Acetabular cup design influences deformational response in total hip arthroplasty basic research. Clin. Orthop. Relat. Res. 471, 403–409. https://doi.org/10.1007/s11999-012-2553-7

Ong, K.L., Rundell, S., Liepins, I., Laurent, R., Markel, D., Kurtz, S.M., 2009. Biomechanical modeling of acetabular component polyethylene stresses, fracture risk, and wear rate following press-fit implantation. J. Orthop. Res. 27, 1467–1472. https://doi.org/10.1002/jor.20918

Otten, V.T.C., Crnalic, S., Röhrl, S.M., Nivbrant, B., Nilsson, K.G., 2016. Stability of Uncemented Cups - Long-Term Effect of Screws, Pegs and HA Coating: A 14-Year RSA Follow-Up of Total Hip Arthroplasty. J. Arthroplasty 31, 156–161. https://doi.org/10.1016/j.arth.2015.07.012

Postak, P.D., Rosca, M., Greenwald, A.S., 2009. Do thin acetabular shells increase the disassociation risk of ceramic liners? J. Bone Jt. Surg. - Ser. A 91, 129–133. https://doi.org/10.2106/JBJS.I.00529

Schmidig, G., Patel, A., Liepins, I., Thakore, M., Markel, D.C., 2010. The effects of acetabular shell deformation and liner thickness on frictional torque in ultrahigh-molecular-weight polyethylene acetabular bearings. J. Arthroplasty 25, 644–653. https://doi.org/10.1016/j.arth.2009.03.020

Small, S.R., Berend, M.E., Howard, L.A., Tunç, D., Buckley, C.A., Ritter, M.A., 2013. Acetabular Cup Stiffness and Implant Orientation Change Acetabular Loading Patterns. J. Arthroplasty 28, 359–367. https://doi.org/10.1016/j.arth.2012.05.026

Spears, I.R., Pfleiderer, M., Schneider, E., Hille, E., Morlock, M.M., 2001. The effect of interfacial parameters on cup-bone relative micromotions A finite element investigation. J. Biomech. 34, 113–120. https://doi.org/10.1016/S0021-9290(00)00112-3

Squire, M., Griffin, W.L., Mason, J.B., Peindl, R.D., Odum, S., 2006. Acetabular Component Deformation with Press-Fit Fixation. J. Arthroplasty 21, 72–77. https://doi.org/10.1016/j.arth.2006.04.016

van Ladesteijn, R., Leslie, H., Manning, W.A., Holland, J.P., Deehan, D.J., Pandorf, T., Aspden, R.M., 2018. Mechanical Properties of Cancellous Bone from the Acetabulum in Relation to Acetabular Shell Fixation and Compared with the Corresponding Femoral Head. Med. Eng. Phys. 1–7.

Wähnert, D., Hoffmeier, K.L., Stolarczyk, Y., Fröber, R., Hofmann, G.O., Mückley, T., 2011. Evaluation of a customized artificial osteoporotic bone model of the distal femur. J. Biomater. Appl. 26, 451–464. https://doi.org/10.1177/0885328210367830

Widmer, K.H., Zurfluh, B., Morscher, E.W., 2002. Load Transfer and Fixation Mode of Press-fit Acetabular Sockets. J. Arthroplasty 17, 926–935. https://doi.org/10.1054/arth.2002.34526

Winter, W., Karl, M., 2014. Basic Considerations for Determining the Amount of Press Fit in Acetabular Cup Endoprostheses as a Function of the Elastic Bone Behavior. Biomed. Tech. 59, 413–420. https://doi.org/10.1515/bmt-2014-0039