Received: 3 September 2021 | Revised: 5 November 2021 | Accepted: 20 November 2021

DOI: 10.1002/jor.25232

RESEARCH ARTICLE

Journal of Orthopaedic Research®

Influence of acetabular cup thickness on seating and primary stability in total hip arthroplasty

Miriam Ruhr[1] | **Johanna Baetz**[1] | **Klaus Pueschel**[2] | **Michael M. Morlock**[1]

[1]Institute of Biomechanics, Hamburg University of Technology, Hamburg, Germany

[2]Department of Legal Medicine, University Medical Center Hamburg-Eppendorf, Hamburg, Germany

Correspondence
Miriam Ruhr, Institute of Biomechanics, Hamburg University of Technology, Denickestraße 15, Hamburg 21073, Germany.
Email: miriam.ruhr@tuhh.de

Funding information
DePuy Synthes

Abstract

Insufficient primary stability of acetabular hip cups is a complication resulting in early cup loosening. Available cup designs vary in terms of wall thickness, potentially affecting implant fixation. This study investigated the influence of different wall thicknesses on the implantation process and the resulting primary stability using excised human acetabula. Implantations were performed using a powered impaction device providing consistent energy with each stroke. Two different wall thicknesses were compared in terms of seating progress, polar gap remaining after implantation, bone-to-implant contact area, cup deflection, and lever out moment. Thin-walled cups showed higher lever out resistance ($p < 0.001$) and smaller polar gaps ($p < 0.001$) with larger bone contact toward the dome of the cup ($p < 0.001$) compared to thick-walled cups. Small seating steps at the end of the impaction process were observed if a high number of strokes were needed to seat the cup ($p = 0.045$). A high number of strokes led to a strain release of the cup during the final strokes ($p = 0.003$). This strain release is indicative for over-impaction of the cup associated with bone damage and reduced primary stability. Adequate cup seating can be achieved with thin-walled cups with lower energy input in comparison to thicker ones. Thin-walled cups showed improved primary stability and enable implantation with lower energy input, reducing the risk of over-impaction and bone damage. Additional strokes should be avoided as soon as no further seating progress has been observed.

KEYWORDS

impaction process, over-impaction, powered impaction, primary stability, wall thickness

1 | INTRODUCTION

Implant loosening, especially on the acetabular side, is one of the main revision reasons for hip endoprostheses.[1–3] To avoid implant loosening at an early stage after surgery, high micromotion, which prevents bone ingrowth into the porous coating of press-fit cups, has to be avoided.[4,5] Failure of long-term stability is usually due to osteolysis, which has been associated with wear particles.[6] It has been shown that high primary stability plays a role also for long-term survival[7,8] and such it is critical for preventing revision surgeries.

The primary stability of press-fit cups is achieved by the friction between the cup and the bone in contact. It is influenced by the roughness of the surface as well as the radial forces between cup and bone resulting from the implantation process.[9–11] Increased primary stability has been demonstrated for high bone mineral density (BMD) and high press-fits.[12–14] Different surface finishes of the cup were also found to influence primary stability,[15,16] but little is known about the direct influence of cup stiffness, which is highly dependent on the wall thickness. Cup wall thickness in commonly used press-fit cups varies between 4 and 8 mm depending on the available bearing articulations or whether the cup is pre-mounted or not.[17] Thin-walled cups provide the opportunity to minimize bone loss and the use of larger heads, which increase the technical range of motion, while the risk of dislocation is only theoretically reduced. Thin-walled cups were shown to exhibit high deformations which can positively influence primary stability. In synthetic bone models, these high deformations occur already for small impaction forces.[17–20]

Besides patient- and implant-related factors, the surgeon plays a crucial role for the success of total hip arthroplasty (THA).[2,21] Clinically, impaction is usually performed with a mallet, which allows for a wide range of variations. The number and intensity of the applied strokes are highly subjective and depend on the bone quality, the press-fit, and the cup design. Cavity preparation, cup orientation, and impaction forces have been shown to influence primary cup stability.[16,22–24] High impaction energies were shown to improve primary stability, while excessive impaction in terms of energy amount and number of strokes should be avoided.[25,26] An influence of the surrogate density on the impaction process has been demonstrated,[26] but the influence of the cup design has not yet been considered.

The purpose of the present study was to investigate the impaction process and the primary stability of two cup designs with different wall thicknesses in human acetabula. In particular, cup deformation, seating process, and resulting bone-to-implant contact were analyzed and related to the primary stability after implantation.

2 | METHODS

The study was performed on the pelvic bone of five human donors aged between 65 and 73 years (mean = 69.2 ± 2.6 years, $m/f = 2/3$). All acetabula were excised via triple osteotomy and stored at −30°C.[27] The study was approved by the Ethics Commission of the Medical Association Hamburg (PV5098).

Initial CT scans (120 kV, 0.4 mm slice thickness, Brilliance 16, Philips) of each acetabulum were recorded with a calibration phantom (QSA, QRM). Hounsfield units were converted to BMD (Structural Insight 3, University Medical Center Schleswig-Holstein[28]). All CT scans were resampled to a voxel size of $0.4 \times 0.4 \times 0.4\ \text{mm}^3$ and the mean acetabular BMD was calculated (AVIZOLite 9.7.0, Thermo Fisher Scientific).[29]

Cup implantation was performed using standard Pinnacle Sector cups with Gription coating and a modified version of it with a thinner wall thickness (standard: ~4 mm wall thickness, modified: ~3 mm, Depuy Synthes; Figure 1). Both cup designs were distributed among the acetabula to obtain similar BMD. Cups were templated with the

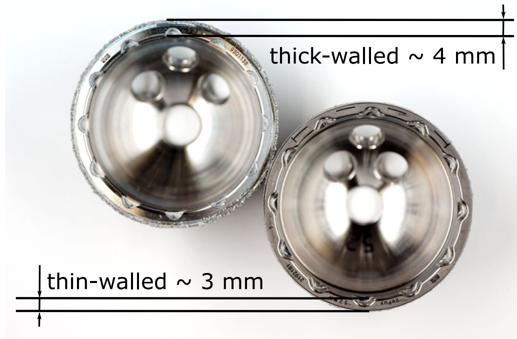

FIGURE 1 The thin-walled and the thick-walled cup design compared in the present study

assistance of an experienced surgeon. The native abduction and anteversion angles were extracted from initial scans (TraumaCAD, Brainlab AG) and used to align with the pelvic orientation to embed the acetabula perpendicular to the desired impaction axis (Technovit4004, Kulzer).

Reaming of the acetabula was performed according to the surgical instructions and the planned cup size. The cavity was under-reamed by 1 mm (nominal press-fit: 1 mm) for the thick-walled cups, while reaming line-to-line for the thin-walled cups (nominal press-fit: 0.5 mm). Since only 1 mm reamer increments were available, the present study was limited to the use of the different nominal press-fits as specified in the surgical instructions. All cups were implanted using a powered impactor applying a consistent impaction energy in the single stroke mode (1 Hz, 3.5 J, Kincise®, Depuy Synthes;[30] Figure 2). Real-time tracking of the implantation was performed with a DIC system (ARAMIS 3D Camera, MV100, GOM). Impaction was stopped when no further cup seating occurred (less than 0.05 mm movement with a stroke). The powered impactor was mounted in a rig and loaded with a weight of 5 kg to ensure a consistent and user-independent setup. After the completion of the implantation process, the cups were extracted. The cavity was re-reamed an additional 2 mm, removing the previous compacted bone[31] and a second implantation of subsequent cup size was performed.

2.1 | Cup deflection

Cup deflection during and after implantation was determined by strain measurements. Four strain gauges (EA-06-062AQA-350/E, Vishay) were bond to the inner cup surface at 90° (Figure 2) according to the expected elliptical deformation pattern.[32,33] The cups were oriented with two opposing strain gauges at the expected locations of maximum strain. Strain was recorded at a sampling frequency of 100 Hz (NI 9222 & Labview, National Instruments). Since the last strokes led to a release in strain, the difference between the maximum strain and the strain after the last stroke was calculated. The final strain was assessed 10 min after impaction, when most relaxation due to the viscoelasticity of the bone has already occurred.[34]

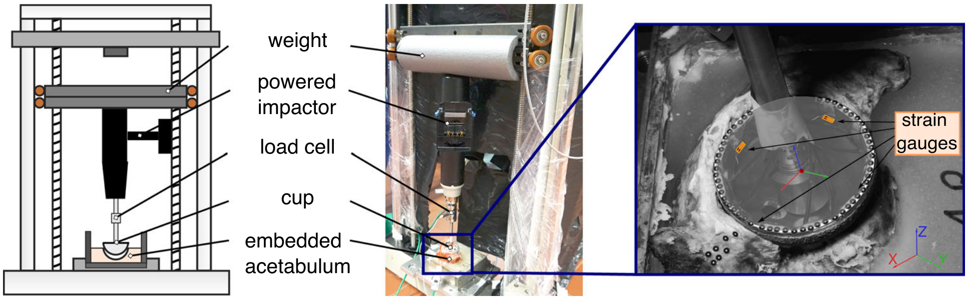

FIGURE 2 The cups were implanted in excised and embedded acetabula. Cup implantation was performed with a powered device mounted in a rig and loaded with a weight of 5 kg. Cup seating and deformation were analyzed using marker tracking with a DIC system. All cups were prepared with four strain gauges at 90° on the inner cup surface

To validate the cup deflection determined from the strain gauge measurements, DIC measurements of the entire cup rim were also performed to determine the deformation. The distance between each marker on the cup rim and the cup center was calculated (Figure 2). Deformation was defined as the change in distance between the initial and the deflected state 10 min after the last stroke analogous to the strain gauge measurements.

2.2 | Cup seating

The cup seating curve of each implantation was evaluated in detail from the DIC recordings afterwards. The center and the entrance plane of the cup were calculated by fitting a circle to all rim markers (Figure 2). The coordinate system was defined based on the initial state of the cup with the cup center as the point of origin and the cup entrance plane as the *XY*-plane. The motion of the cup center in the *z*-direction was calculated and the seating for each stroke was extracted as the change in distance from the initial state. An exponential function $f = a \cdot e^{-\frac{x}{\tau}} + c$ was fitted to the amount of seating for each stroke. The seating curve coefficient τ is used to describe the seating progress. Seating curves with strongly reduced amounts of seating during the latest strokes are characterized by a small seating curve coefficient, whereas a high coefficient is indicative for a more continuous seating process. The exact number of strokes used for final seating was determined using a load cell (9333A, Kistler), which was mounted in the impactor. The triggering threshold was set to 500 N (NI 9222 & Labview, National Instruments).

2.3 | Bone – Implant contact

Contact analysis between bone an implant was performed based on aligned 3D laser scans of the cup, the acetabulum after reaming, and after cup implantation (Handyscan 3D, Creaform, Ametek). The press-fit distribution was determined by analyzing the interference between implanted cup with respect to the reamed cavity (PolyWorks|Inspector 2019, InnovMetric Software Inc.; Figure 3A). The mean press-fit and contact area were determined for the whole outer cup surface as well as separately for five different equally high regions from dome to entrance plane. The polar gap was calculated as the distance of two spheres fitted to the outer cup surface and the reamed cavity based on a pure least-squares approach (Figure 3B).

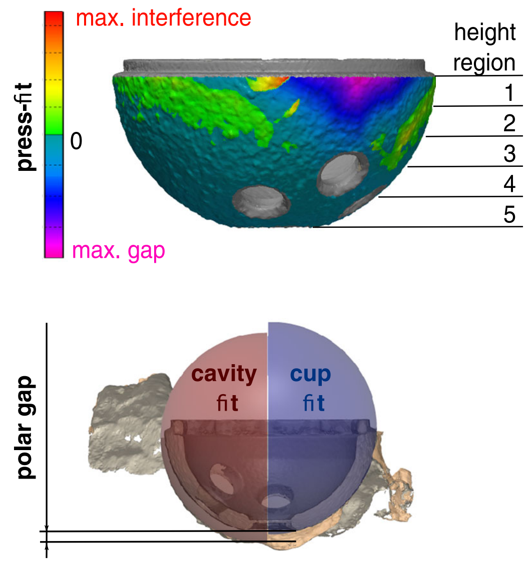

FIGURE 3 Contact analysis using the aligned laser scans of cup and bone. (A) The press-fit was calculated for the whole outer cup surface as well as for five different height regions. (B) The polar gap was defined based on spherical best-fits of the acetabulum and the implanted cup

2.4 | Primary stability

All cups were quasi-statically levered out by applying a force at a 90-degree angle to the impactor axis using a tensile testing machine (Z010, Zwick Roell). The acetabula were oriented so that the axis of maximum deformation was perpendicular to the direction of the lever out force. The force was applied at a constant rate of 0.05 mm/s and stopped when the force dropped by 75%. The maximum force was multiplied by the lever arm to calculate the lever out moment as a measure for the primary stability.

2.5 | Statistical analysis

Statistical analysis was performed using R (RStudio, RStudio PBC). A Type I error level of 0.05 was used for all tests of significance (significance at $p < 0.05$). The differences between thin-walled and thick-walled cup designs were analyzed with an unpaired *t*-test for normally distributed data; if the normal distribution was violated, a Mann–Whitney *U*-test was performed. Linear dependencies were tested with Pearson correlations for normally distributed data; otherwise, Spearman's rho correlations were performed.

3 | RESULTS

3.1 | Cup deflection

Thin-walled cups exhibited a significantly higher final strain than the thick-walled cups (thin-walled: 290 µm/m (207–1672 µm/m); thick-walled: 182 µm/m (29–467 µm/m); $p = 0.007$). No difference in BMD was observed between the cup design groups since an even distribution of the cup designs was aimed for (thin-walled: 269 ± 57 mgHA/cm^3; thick-walled: 287 ± 42 mgHA/cm^3; $p = 0.445$). Final strain increased with BMD for thin-walled cups ($p = 0.031$, $R^2 = 0.76$), while no influence was seen for thick-walled cups ($p = 0.538$, $R^2 = 0.04$; Figure 4A). Only incomplete data on cup strain could be recorded for 4 of the 20 implantations. One strain gauge each was damaged during the impaction of three cups, and no strain could be recorded for one cup. The DIC system achieved a median coverage of the cup rim of 272.3° (128.5°–281.9°), missing parts were hidden by the bone and the impactor. The maximum cup strain (from strain gauges) was compared to the maximum cup deformation (determined with the DIC system) for all cups, revealing a strong linear relationship for both cup designs ($p < 0.001$, $R^2 = 0.83$; Figure 4B).

3.2 | Cup seating

The thin-walled cups showed more seating during the initial strokes of the impaction process with only little further seating toward the end of the impaction process (Figure 5A). This behavior is represented by the higher seating curve coefficient for the thick-walled cups (3.85 ± 2.30) in comparison to the thin-walled cups (2.61 ± 1.35; $p = 0.168$). A higher number of strokes was needed for cups with high seating curve coefficients ($p = 0.045$, $R^2 = 0.22$). The strain release increased with the number of strokes with a larger strain decrease for the thick-walled cups ($p = 0.007$, $R^2 = 0.67$) compared to the thin-walled cups ($p = 0.017$, $R^2 = 0.53$; Figure 5B).

3.3 | Bone – Implant contact

The press-fit distribution between cup and bone differed between the two cup designs ($p < 0.001$). The occurrence of small press-fits was more pronounced for the thin-walled cups while higher press-fits were observed for the thick-walled cups. The total contact area was similar for the two cup designs ($p = 0.949$) but differences between the cups were observed for the different height regions (Figure 6A). The top and middle regions were similar (regions 1: $p = 0.728$, 3: $p = 0.355$, 4: $p = 0.306$), but differences were seen in the second and fifth regions. In region 2, the thick-walled cups had more contact ($p = 0.004$) and in region 5 less ($p < 0.001$). The amount of press-fit had no effect on cup strain (thin-walled: $p = 0.538$, $R^2 = 0.057$, thick-walled: $p = 0.889$, $R^2 = 0.003$). For the thick-walled cups, a tendency of press-fit increase with BMD was observed ($p = 0.156$, $R^2 = 0.235$), which was not seen for the thin-walled cups ($p = 0.434$, $R^2 = 0.078$). Cups with small polar gaps showed a lower strain release during the impaction process ($p = 0.045$, $R^2 = 0.22$; Figure 6B). Thin-walled cups were seated more completely than thick-walled cups (polar gap thin: 0.76 ± 0.52 mm, thick: 2.01 ± 0.78 mm; $p < 0.001$).

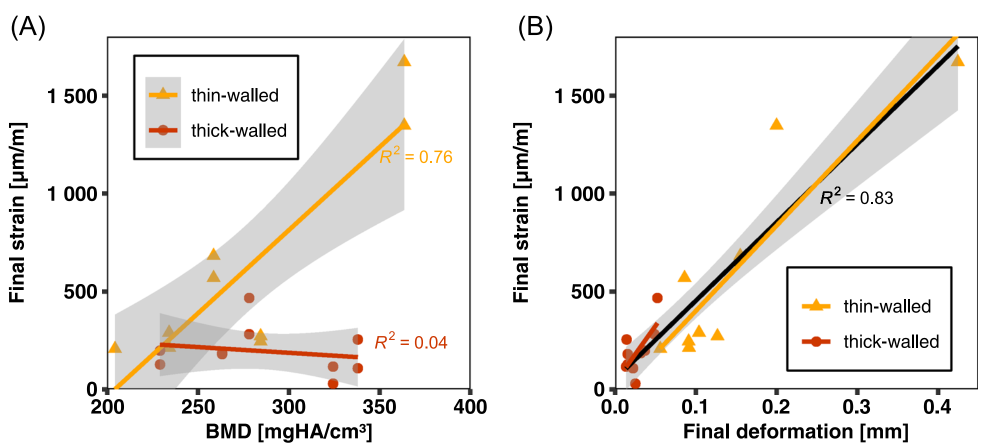

FIGURE 4 Deflection analysis of the cup designs. (A) The final strain increased for the thin-walled cups at high BMDs ($p = 0.031$). (B) A strong linear relation was observed between cup deflection and deformation ($p < 0.001$). BMD, bone mineral density

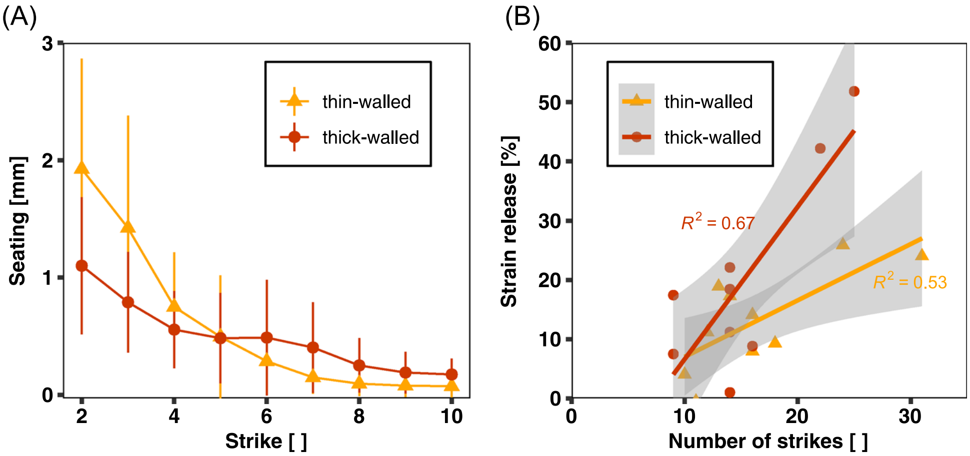

FIGURE 5 Seating analysis of the cup designs. (A) Cup seating for consecutive strikes showing different seating behavior for the cup designs (thin: $\tau = 3.85 \pm 2.30$; thick: 2.61 ± 1.35; $p = 0.168$; note: only the first 10 strokes are shown). (B) Increasing strain release for a higher number of strikes (thick-walled: $p = 0.007$; thin-walled: $p = 0.017$)

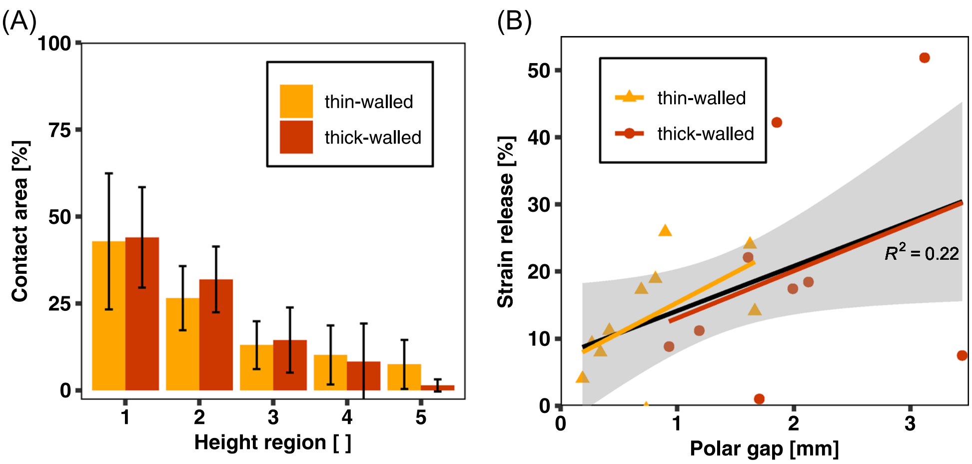

FIGURE 6 Contact analysis of the cup designs. (A) The contact area within the different height regions decreased toward the pole (1: cup entrance plane, 5: cup pole). (B) Increased strain release during the impaction process for high remaining polar gaps ($p = 0.045$)

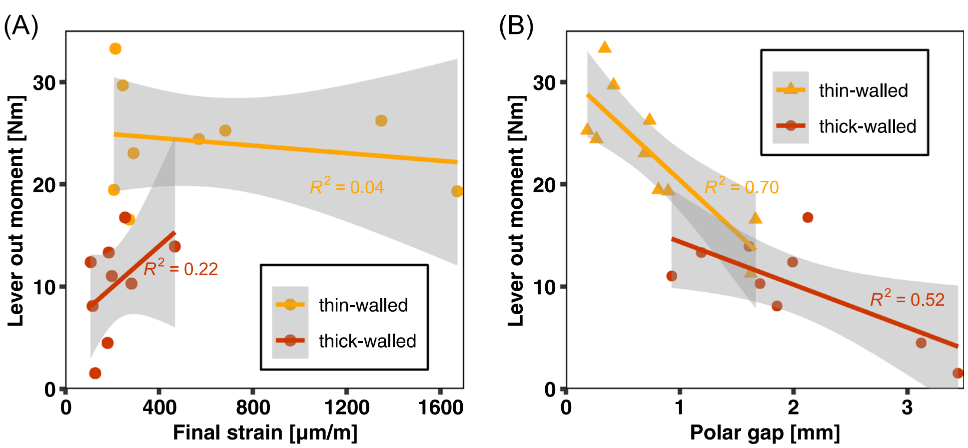

FIGURE 7 Primary stability analysis of the cup designs. (A) The lever out moment increased with higher cup strains for the thick-walled cups ($p = 0.178$). The lever out moment of the thin-walled cups was on a higher level ($p < 0.001$) regardless of the cup strain ($p = 0.678$). (B) The polar gap correlated with the lever out moment for both cup designs (thin-walled: $p = 0.003$; thick-walled: $p = 0.029$)

3.4 | Primary stability

The lever out moments were significantly higher for the thin-walled cups than for the thick-walled cups ($p < 0.001$). They tended to increase with the final strain for the thick-walled cups ($p = 0.178$, $R^2 = 0.22$), whereas they were constantly high for the thin-walled cups ($p = 0.678$, $R^2 = 0.04$; Figure 7A). Primary cup stability improved for small polar gaps with a higher influence for the thin-walled cups ($p = 0.003$, $R^2 = 0.70$) in comparison to the thick-walled cups ($p = 0.029$, $R^2 = 0.52$; Figure 7B).

4 | DISCUSSION

The purpose of the current study was to assess the effect of different wall thicknesses on cup seating and primary stability. The results have shown that cup seating is highly important for good primary stability which was found to be improved for the thin-walled cup design. A sufficient seating depth leading to a good press-fit should be achieved, but excessive or over-impaction must be omitted. The importance of an adequate energy input during the impaction process to ensure sufficient seating depth is highlighted by this study. The thin-walled cup design was found to exhibit higher deformations but to be less susceptible to inadequate fixation with the chosen energy level. The usage of a powered impaction tool enables energy-controlled impaction and reduces surgical variations.

Cup deflection was recorded using two different measurement methods. Strain gauges allow to accurately determine cup deflection from the recorded strains but are limited by the visual rotational cup alignment to the bone and local confinement to the strain gauge measurement grid. Misorientation during positioning or cup implantation and/or the irregular acetabular shape[32,33] could result in missing the maximum and minimum peak strain. Strain gauge measurements were therefore double-checked with the cup deformation determined from the DIC recordings. Deformation was measured along the visible cup rim for about 250°, achieving a better spatial coverage as the four strain gauges but still not a complete coverage. The similarity of both methods for measuring the cup deflection could be demonstrated.

Maximum strains were higher for thin-walled than for thick-walled cups. This coincides with the higher deflections due to the lower cup stiffness of the thin-walled cups[19,33] and results in lower contact stresses to the bone. The previously demonstrated correlation of cup deflection and lever out moment[18] was in the present study only demonstrated for the thick-walled design. The thin-walled cups were found to be more robust exhibiting a rather constant high primary stability. This highlights the interaction between cup deflection and cup thickness for primary stability. Despite the improved primary stability, the high deformations can compromise the insertion of hard liners and the bearing tribology of polyethylene (PE) liner.[35,36] A possible deformation of a PE liner could affect the liner locking and the joint lubrication. The maximum measured deformation of the thin-walled cups was 0.425 mm, about eight times higher than the maximum measured deformation of the thick-walled cups of 0.052 mm. The insertion of hard liners can lead to a significant reduction in deformation.[18] High cup deformations do not necessarily lead to improper liner seating or excessive liner deformation but certainly, make the liner insertion more difficult. A detailed analysis of the time-dependent cup deformation could also help to assess whether liner insertion may benefit from a specific relaxation time.

The phenomenon of over-impaction to occur for a high number of strokes, resulting in reduced lever out moments, has also been reported by other authors.[26] A high number of strokes was associated with a small seating progress over many strokes toward the end of impaction associated with larger strain release pronounced for the thick-walled cup. It is speculated that the final strokes with small seating progress reduced primary stability due to increased bone damage at the interface without increasing press-fit.[26,37] Excessive or over-impaction is critical for primary stability and should be omitted. Thin-walled cups benefit from their faster converging seating progress. Since the seating progress cannot be closely monitored during surgery, higher seating steps would facilitate the visible tracking of cup seating. The use of higher energies seems to have a positive effect on cup seating, but possibly increases the risk of bone damage.[25]

Cup implantation is also influenced by the acetabular cavity. High BMDs[20,32,33] as well as high press-fits[18,32] are expected to increase the cup deflection. The two cup designs showed different behaviors with increasing BMDs. The deflection of the thin-walled cups increased at higher BMDs due to the higher reaction forces of the stiffer bone. In contrast, strain of the thick-walled cups was not influenced by BMD. An influence of the measured press-fit itself could not be detected for the individual cup designs. Since the nominal press-fit was fixed within each cup design group, variations due to the manual reaming process should not have affected the cup deflection to the same extent as bone quality. Thin-walled cups were found to distribute the radial cup forces to the surrounding bone more homogeneously, possibly reducing the stress-shielding effect while improving osseointegration.[38,39] This is the result of the combined effect of the different cup stiffness and the difference in nominal press-fits, indicating that the nominal press-fit should be specific for each cup design.

The size of the polar gap as the result of the implantation process, combines the previously discussed parameters and is the variable related most to the lever out moment and thus to primary stability. Small polar gaps were associated with high contact areas, which positively affect cup deformation.[12,13] The polar gap was significantly higher for thick-walled cups than for thin-walled cups. The large remaining polar gaps indicate that the applied energy of 3.5 J was not sufficient to further deform or seat the thick-walled cup for higher BMDs and thus limited the effective press-fit. The thick-walled cup designs might benefit from higher impaction energies or a smaller nominal press-fit, as used by some surgeons. A line-to-line reaming approach for the thicker cup was not analyzed in the present study. Previous studies have shown the benefits of small polar gaps below 2 mm,[40,41] which were not achieved with the thick-walled cups in this study. When attempting to reduce the polar gap, bottoming-out of the cup must be avoided before maximum peripheral contact is achieved.[42]

The results of this study do only apply to the two designs investigated. It is, however, expected that cups with different cup thicknesses generally would behave in a similar way.

5 | CONCLUSION

The thin-walled cup design investigated in this study benefits from the smaller polar gaps achieved with the energy of the powered impactor in contrast to the thick-walled cup design thus leading to higher primary stability. Impaction energy might have to be adapted to different cup designs to achieve full seating. Impaction should be stopped when full cup seating is achieved to omit over-impaction resulting in bone damage instead of press-fit improvement, negatively affecting primary stability.

ACKNOWLEDGMENTS

The authors would like to thank Frank Lampe for surgical assistance during the preparation and conduct of the study. The authors thank Depuy Synthes for providing the prosthesis components, surgical tools, and financial support. All experimental studies were performed at the University Medical Center Hamburg-Eppendorf (UKE) and the Hamburg University of Technology. Open Access funding enabled and organized by Projekt DEAL.

CONFLICT OF INTERESTS

M. Morlock is a paid consultant of DePuy Synthes and obtains research support as a Principal Investigator from Ceramtec, DePuy and Beiersdorf. He obtains speaker's fees from Aesculap, Ceramtec, DePuy, Zimmer, Peter Brehm, Corin and Mathys and is in the editorial board "Trauma und Berufskrankheit."

AUTHOR CONTRIBUTIONS

Miriam Ruhr: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft, Visualization. Johanna Baetz: Methodology, Writing – review and editing. Klaus Pueschel: Methodology, Resources. Michael M. Morlock: Conceptualization, Methodology, Supervision, Funding acquisition, Resources, Writing – review and editing. All authors have read and approved the submitted manuscript.

ORCID

Miriam Ruhr http://orcid.org/0000-0002-1832-3305

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How to cite this article: Ruhr M, Baetz J, Pueschel K, Morlock MM. Influence of acetabular cup thickness on seating and primary stability in total hip arthroplasty. *J Orthop Res*. 2022;40:2139-2146. doi:10.1002/jor.25232