Acta Med. Okayama, 2021
Vol. 75, No. 1, pp. 71-77

Acta Medica
Okayama

http://escholarship.lib.okayama-u.ac.jp/amo/

Original Article

The Thickness of the Medial Wall of the Acetabulum Prevents Acetabular Fracture during the Insertion of a Cementless Cup in Total Hip Arthroplasty: A Biomechanical Study

Tomoaki Sanki, Tomonori Tetsunaga*, Takayuki Furumatsu, Kazuki Yamada, Yoshi Kawamura, and Toshifumi Ozaki

Department of Orthopaedic Surgery, Okayama University Graduate School of Medicine, Dentistry and Pharmaceutical Sciences, Okayama 700-8558, Japan

Intra-operative acetabular fracture is a total hip arthroplasty complication that can occur during cementless cup insertion, especially in osteoporotic patients. We conducted this biomechanical study to investigate the impact resistance of the acetabulum with simulated bones of different density by drop-weight impact testing. Low- and high-density polyurethane foam blocks were used as osteoporotic and healthy bone models, respectively. Polyurethane blocks were used as the acetabular cancellous bone. Composite sheets were used as the acetabulum's medial cortex. The testing revealed that the osteoporotic bone model's impact resistance was significantly lower than that the healthy bone model'. In the healthy bone model, even thin acetabular cancellous bone with ≥ 1 mm acetabulum medial cortex was less likely to fracture. In the osteoporotic bone model, fracture was possible without ≥ 1 mm medial cortex of the acetabulum and thick acetabular cancellous bone. Although impaction resistance differs due to bone quality, the impaction resistance in this osteoporotic bone model was equivalent to that healthy bone model's when a thick medial wall was present. To avoid intra-operative acetabulum fracture, surgeons should consider both the bone quality and the thicknesses of the medial cortex and acetabular cancellous bone.

Key words: intra-operative acetabular fracture, drop weight impact testing, total hip arthroplasty, impact resistance

Total hip arthroplasty (THA) is a common intervention in orthopedic surgery that functions to provide relief of pain [1]. However, a THA also poses a risk of complications [2,3] including aseptic loosening of the acetabular cup [4] and intra-operative fractures [5], especially in osteoporotic patients. The press-fit technique is necessary to obtain primary stability for a cementless acetabular cup component [6] because primary stability has been identified as a crucial factor to achieve osseointegration and long-term survival of the acetabular cup component [7-11]. A press-fit also needs increased impaction force during the insertion of the acetabular cup; impaction force that is too great can cause an intra-operative acetabular fracture [12,13]. Intra-operative acetabular fractures occur mainly during the insertion of cementless acetabular cup components.

Haidukewych *et al*. [14] reported that the intra-operative incidence of an acetabular fracture is 0.4%, and they noted that osteoporotic bone is a known risk factor. Hasegawa *et al*. [15] stated that peri-prosthetic occult fractures of the acetabulum occur relatively frequently during press-fit impaction, 8.4% incidence. The medial wall of the acetabulum consists of medial cortex and acetabular cancellous bone. This area receives impaction

---

Received March 27, 2020; accepted October 9, 2020.
*Corresponding author. Phone : +81-86-235-7273; Fax : +81-86-223-9727
E-mail : tomonori_t31@yahoo.co.jp (T. Tetsunaga)

Conflict of Interest Disclosures: No potential conflict of interest relevant to this article was reported.

during the insertion of cementless acetabular cup components. We tested the following hypothesis herein: (1) The thickness of the medial wall is associated with resistance to impaction. (2) In patients with healthy bone, a thin medial wall due to excessive cup reaming maintains the resistance to impaction. (3) Avoiding excessive cup reaming and preservation of the thickness of the medial wall would help prevent intra-operative fractures in patients with osteoporotic bone.

Although some studies have indicated that bone fragility is a risk factor for intra-operative acetabulum fracture [14, 15], there are no experimental biomechanical reports regarding this finding. In this study, we performed drop-weight impact testing under different conditions to investigate the resistance of the acetabulum during the insertion of an acetabular cup implant.

Methods

Bone model. In this biomechanical study, T.S. and T.T. created an original acetabular model using simulated bones. High-density Sawbones® (block #1522-04; density, 0.48 g/cm^3; compressive strength, 18 Mpa; Sawbones, Malmö, Sweden) and low-density Sawbones® (block #1522-03; density, 0.32 g/cm^3; compressive strength, 8.4 Mpa; Sawbones) were used as simulated bones. Sawbones provides polyurethane foam blocks that simulate cancellous bone in reproducible, clean, and artificial materials. Sawbones also provides composite sheets that simulate cortical bone (#3401-07 or #3401-01; density, 1.64 g/cm^3; compressive strength, 157 Mpa). We used the low-density Sawbones as a model of relatively fragile osteoporotic bones (group O), and high-density Sawbones as relatively strong normal bones (group N). We created a hemispherical cavity (52 mm dia.) and 2, 5, or 8 mm thickness of the acetabular cancellous bone in each block to represent the acetabulum. We used 1- or 2-mm-thick composite sheets and bonded them to the blocks to represent the medial cortex of the acetabulum.

The medial wall of the acetabulum consists of the medial cortex and acetabular cancellous bone. We prepared three types of bone models using two different Sawbones (high- or low-density). The type 1 bone model was made from a Sawbones block without a composite sheet. The type 2 bone model was made from a Sawbones block with the 1-mm-thick composite sheet, and the type 3 model was made from a Sawbones block with the 2-mm-thick composite sheet. Five samples of each bone model type were prepared in this study.

Experimental device. Figure 1A illustrates the experimental device used in this study. We used the CEAST 9340 droptower impact system (Instron, Canton, MA, USA) to perform the drop-weight impact testing. The experimental set-up that we specifically manufactured for this study was designed to hold each block on the test platform during the testing (Fig. 1B). Three-dimensional press-fit acetabular component implants (GS cup; Teijin Nakashima Medical Co., Okayama, Japan) were used in this study. The external diameter of the implants was 50 mm.

The acetabular cup was inserted into the cavity representing the acetabulum. The external diameter of the cavity was 52 mm in order to fit the implant into the cavity considering the thickness of the porous coating of the implant. A metal liner was put into the acetabular cup to receive the drop-weight impaction. The mass drop weight was 3.0 kg and had a displacement amplitude of 300 mm. The mass drop weight and height were chosen to generate force magnitudes of 12,000 ± 700 N. The average force of the manual impact of a hammer used by the hip surgeons (T.S. and T.T.) with the Sawbones held on the testing platform was approx. 12,000 N. The force induced by the mass falling on the head of the cup was recorded using a force sensor (CEAST instrumented striker; Instron). The output voltage file was post-processed by a software routine in Visual IMPACT (ver. 6, Instron).

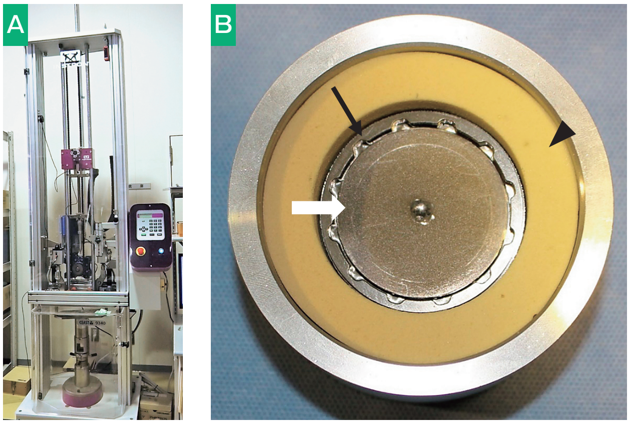

Fig. 1 Experimental device. **A**, CEAST 9340 droptower impact system (Instron); **B**, Original jig to hold the Sawbones block. *Black arrow*: Acetabular cup. *White arrow*: Liner. *Black triangle*: Sawbones (representing the acetabulum).

Experimental protocol. Drop-weight impact testing was performed under 3 different conditions: in both groups O and N, the testing was performed on the bone model types 1, 2, and 3. In only group N, the testing was performed on bone model types 1, 2, and 3 with an acetabulum (2- or 5-mm acetabular cancellous bone thickness). In only group O, the testing was performed on types 1, 2, and 3 with an acetabulum (5- or 8-mm acetabular cancellous bone thickness). Five samples of each bone model type were tested, and the peak force was measured with a force sensor.

Statistical analysis. We used the Statistical Package for the Social Sciences (SPSS, ver. 20.0; IBM SPSS Statistics for Windows, Armonk, NY) for the statistical analysis. The Mann-Whitney *U*-test was used to assess the differences in peak force in each bone model type between groups O and N. We performed a one-way analysis of variance (ANOVA) to assess the differences in peak force between bone model types 1, 2, and 3 within the same group. P-values <0.05 were considered significant.

Results

Figure 2 shows typical representative signals recorded by the force sensor during the mass drop-weight testing, and Table 1 summarizes the peak force data for the three bone model types of the two Sawbones with different densities of bones in groups O and N. The impact resistance was significantly increased from bone model types 1 to 3 in both the osteoporotic and normal bones with 5-mm acetabular cancellous bone thickness (both $p<0.001$). The impact resistance values for bone model types 1 and 2 in group O were significantly lower than those in group N (both $p<0.001$). The impact resistance for type 3 in group O was equivalent to that in group N ($p=0.862$). The type 1 blocks in groups O and N and type 2 blocks in group O were broken by the testing, which indicated that these blocks could not absorb the impact of a mass drop. The type 2 blocks in group N and the type 3 blocks in groups O and N were not broken.

Figure 3A shows typical representative signals recorded by the force sensor during the mass drop-weight testing

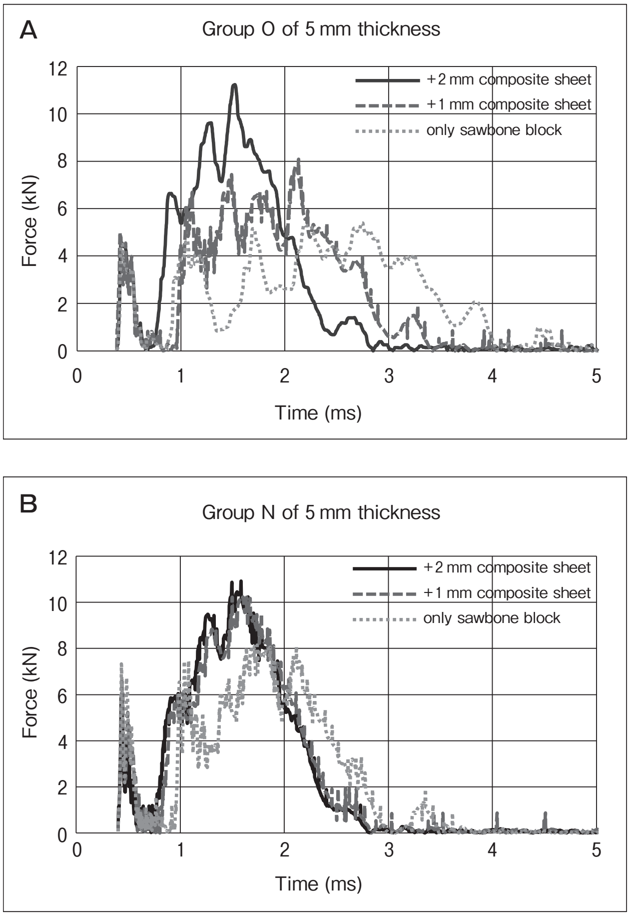

Fig. 2 A, Typical representative signals recorded by the force sensor during the drop-weight impact testing in Group O of 5-mm-thick acetabular cancellous bone; B, Typical representative signals recorded by the force sensor during drop-weight impact testing in Group N of 5-mm thickness. The impact resistance was significantly increased from bone model types 1 to 3 in both the osteoporotic (A) and normal bones (B) with 5-mm acetabular cancellous bone thickness.

Table 1 Peak force data for three types of two different density sawbones of 5 mm thickness

5 mm thickness	group O (n=5)	group N (n=5)	*p*-value
Type 1 (block only)	5427 ± 321 N	8203 ± 271 N	<0.001[a]
Type 2 (block +1 mm composite sheet)	8142 ± 157 N	11471 ± 315 N	<0.001[a]
Type 3 (block +2 mm composite sheet)	11014 ± 217 N	11721 ± 214 N	0.862[a]

All data represented as mean ± standard deviation. [a]Mann-Whitney *U* test of 2-mm acetabular cancellous bone thickness, and Table 2 summarizes the peak force data for the three types of acetabula in Group N with two different thicknesses of acetabular cancellous bone. The impact resistance increased significantly from bone types 1 to 3 in both acetabula (both $p<0.001$). No significant differences were observed in the impact resistance for the type 1, 2, and 3 blocks with the 2-mm and 5-mm acetabular cancellous bone thicknesses ($p=0.481$, 0.352, and 0.435, respectively). The type 1 blocks with the 2-mm and 5-mm acetabular bone thicknesses were both broken in group N. These results indicated that type 1 blocks could not absorb the impact of a mass drop. In contrast to type 1, neither the type 2 blocks nor the type 3 blocks with 2-mm and 5-mm acetabular bone thickness were broken in group N.

Figure 3B shows typical representative signals recorded by the force sensor during the mass drop-weight testing of 8-mm acetabular cancellous bone thickness, and Table 3 summarizes the peak force data for the three types of acetabula in group O with two different thicknesses. The impact resistance increased significantly from bone type 1 to bone type 3 in acetabula of both 5-mm and 8-mm thicknesses (both $p<0.001$). The impact resistance of the types 1 and 2 acetabula in the 8-mm acetabular cancellous bone thickness group was significantly higher than that of the 5-mm acetabula thickness group (both $p<0.001$). There was no significant difference in the impact resistance of the type 3 acetabula between the 5-mm and 8-mm acetabular cancellous bone thickness ($p=0.493$). The type 1 blocks with the 5-mm or 8-mm acetabular cancellous bone thickness and the type 2 blocks with the 5-mm thickness were broken in group O. These results indicated that blocks could not absorb the impact of a mass drop. In contrast, the type 2 blocks with 8-mm thickness and the type 3 blocks with 5-mm or 8-mm acetabular cancellous bone thickness were not broken in group O.

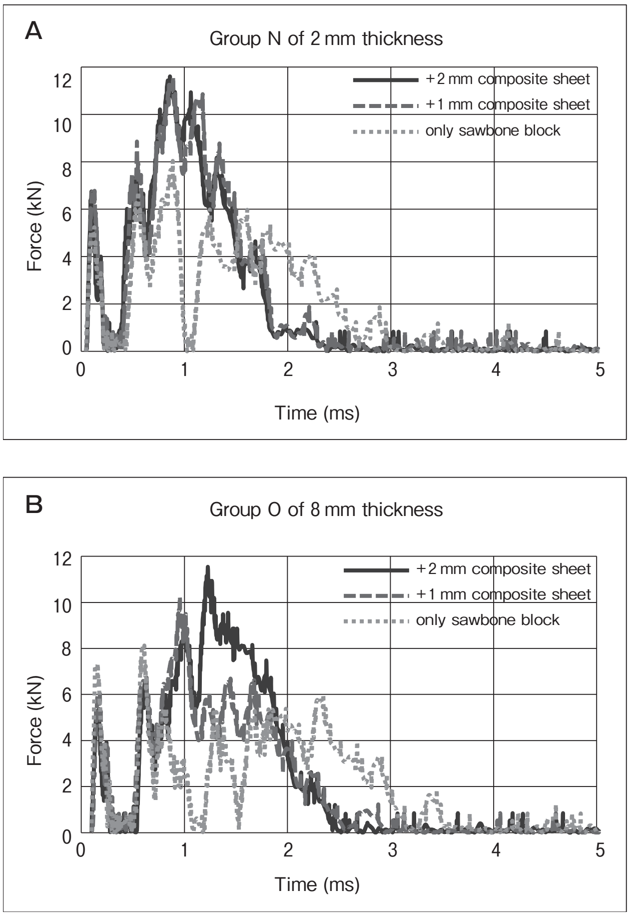

Fig. 3 A, Typical representative signals recorded by the force sensor during drop-weight impact testing in Group N of 2-mm-thick acetabula; B, Typical representative signals recorded by the force sensor during the drop-weight impact testing in Group O of 8-mm-thick acetabula. The impact resistance increased from bone model types 1 to 3 in both the normal (A) and osteoporotic acetabula (B).

Discussion

Our study's 3 major findings were as follows. (1) The

Table 2 Peak force data for three types of two different thickness of acetabulum in group N

	Thickness		*p*-value
	2 mm (n=5)	5 mm (n=5)	
Type 1 (block only)	8082 ± 415 N	8203 ± 271 N	0.481[a]
Type 2 (block +1 mm composite sheet)	10517 ± 440 N	11471 ± 315 N	0.352[a]
Type 3 (block +2 mm composite sheet)	10747 ± 482 N	11721 ± 214 N	0.435[a]

All data represented as mean ± standard deviation. [a]Mann-Whitney *U* test

Table 3 Peak force data for three types of two different thickness of acetabulum in group O

	Thickness		
	5 mm (n = 5)	8 mm (n = 5)	*p*-value
Type 1 (block only)	5427 ± 321 N	8107 ± 326 N	< 0.001[a]
Type 2 (block + 1 mm composite sheet)	8142 ± 157 N	10238 ± 486 N	< 0.001[a]
Type 3 (block + 2 mm composite sheet)	11014 ± 217 N	11049 ± 651 N	0.493[a]

All data represented as mean ± standard deviation. [a]Mann-Whitney *U* test

impact resistance of the osteoporotic bone model was lower than that of the healthy bone model and increased as the thickness of the medial wall increased. (2) When the thickness of the medial wall was maintained by a minimum of reaming, the impact resistance increased, even in the osteoporotic bone model. (3) In the healthy bone model, even when cup reaming caused thinning of the medial wall, sufficient impact resistance was maintained. These results support our hypothesis.

We used low-density Sawbones as a model of relatively fragile osteoporotic bones and high-density Sawbones as a model of relatively strong normal bones in this study. We set the thickness of the medial cortex to 1 or 2 mm, and we set the thickness of the acetabular cancellous bone in osteoporotic bone to 5 or 8 mm and 2 or 5 mm in healthy bones. Since the impaction force varies by manual impaction, we performed drop-weight impact testing by using a droptower system to reproduce the impaction force. In studies that examined the duration of impaction during the insertion of acetabular cup components *in vitro* using drop-weight impact testing with a protocol that is similar to that used in the present investigation, a force magnitude higher than 2,000 N was chosen [16]. In other biomechanical studies, an impact force of 4,000-5,000 N was chosen [17, 18]. In contrast, the typical impact force was different *in vivo* (comprised of intervals between 6,000 and 15,000 N).

Based on their biomechanical study's findings, Michel *et al.* [17] reported that a simple configuration using simulated bones does not take into account the influence of damping that may be encountered during the actual surgical procedure, since the pelvic bone is surrounded by soft tissue and has a large damping effect. In the present study, the average force of manual impact using a hammer by hip surgeons (T.S. and T.T.) under conditions in which the Sawbones were held on a testing platform was approx. 12,000 N (data not shown). We therefore chose values of the mass drop weight and height that would generate force magnitudes of 12,000 ± 700 N.

The peak force of the bone model type 1 block (5 mm thickness) was 5,427 ± 321 N in group O and 8,203 ± 271 N in group N against an impact generating approx. 12,000 N. Under these conditions, the bottom of the Sawbones was broken, and we concluded that the Sawbones could not absorb the impact of a mass drop. When we bonded composite sheet to a Sawbones to represent the medial cortex of the acetabulum, the impact resistance increased depending on the thickness of the composite sheet. The peak force values of the type 3 block (5-mm thickness) were 11,014 ± 217 N in group O and 11,721 ± 214 N in group N, which were not significantly different (Table 1). These results suggest that (1) the impact resistance in osteoporotic bone is lower than that in healthy bone and increases with the thickness of the medial wall, and (2) the medial cortex of the acetabulum contributes to the impact resistance.

The peak force values of the bone model types 1, 2, and 3 with acetabula with two different thicknesses (2 mm and 5 mm) in group N were not significantly different (Table 2). Types 2 and 3 blocks absorbed the impaction of a mass drop with no acetabulum cracking. These results suggest that even if reaming of the acetabulum causes thinning of the medial wall, the risk of fracture would not be high in patients with healthy bone.

In contrast, in group O, the impact resistance of bone model types 1 and 2 with 8-mm thick acetabula was significantly higher than that obtained with the 5-mm-thick acetabula (Table 3). Because of the 2-mm thickness of the medial cortex, the peak force of bone model type 3 was not significantly different between the 5-mm and 8-mm acetabular cancellous bone thicknesses. These results suggest that (1) the bone stock of the acetabular cancellous bone and the thickness of the medial cortex are important in osteoporotic bone, and

(2) when the thickness of the medial wall was maintained by a minimum of reaming, the impact resistance increased, even in osteoporotic bone. In clinical practice, it is important that surgeons determine the thickness of the medial cortex and acetabular cancellous bone in preoperative CT images, as excessive reaming can be evaluated for high fracture risk when an acetabular component is to be implanted in an osteoporotic patient with thin acetabular cancellous bone thickness.

This study had some limitations. First, the biomechanical properties of the human pelvis and Sawbones differ, and there may be differences between our experimental results and the clinical environment. However, simulated bones such as Sawbones could serve as representative models for varying bone quality, which is also a significant factor in resistance to impaction [19], and a consistent polyurethane testing medium has been used in several biomechanical studies [18,20-22]. Second, the external diameters of the implant used in this study and the cavity differed. In clinical practice, when inserting a three-dimensional press-fit acetabular component implant such as a GS cup, we perform the same reaming of the acetabulum. In this study, the external diameter of the cavity was made 2 mm wider than that of the implant considering the thickness of the porous coating, in order to fit the implant into cavity. When the external diameter of the implant and that of the cavity are same, the variance of the impaction force may be different, and this should be investigated in future studies. Third, our study did not investigate the question of what is the sufficient thickness of medial cortex and cancellous bone to absorb the impaction when an acetabular component is implanted. The present experimental parameters consisted of 2 types of bone quality, 2 thicknesses of medial cortex, and three thicknesses of cancellous bone. We did not examine which parameters contribute the most to impaction resistance. This point should be investigated in future studies.

Fourth, the structure of the human acetabulum and that of our model using Sawbones are different. The human pelvis is a three-dimensional structure that is supported by surrounding soft tissues such as muscles and ligaments. It was impossible to reproduce this structure experimentally. In this study, the structure of the acetabulum model was simple because it was necessary to hold the Sawbones block in the original jig to the perform drop-weight impact testing; we were thus able to investigate the impact resistance of Sawbones of different densities by using this simple structural acetabulum model.

The results of this study constitute an *ex vivo* validation of a biomechanical method consisting of simulated bones and drop-weight impact testing. It is unclear whether the present findings can be applied to clinical practice. Although our results did not reveal how great a thickness of the medial wall could avoid acetabular fracture, it seems to be important to consider the fracture risk by measuring the medial wall thickness during pre-operative planning. We did not choose to use human tissues for ethical reasons sine the present method has not been validated. Further studies should be performed in cadavers to test our present findings.

In conclusion, we used drop-weight impact testing to determine the impaction resistance upon the insertion of acetabular cup components. Although the impaction resistance differed due to bone quality, the impaction resistance in the osteoporotic bone model was equivalent to that of healthy bone under the condition of a thick medial wall. To avoid intra-operative acetabulum fracture during a total hip arthroplasty, it is important to consider not only the patient's bone quality but also the thicknesses of the medial cortex and acetabular cancellous bone.

Acknowledgments. Our sincere thanks to Teijin Nakashima Medical Co., Ltd. (Okayama, Japan) for supporting our study.

References

1. Learmonth ID, Young C and Rorabeck C: The operation of the century: total hip replacement. Lancet (2007) 370: 1508–1519.
2. Higa M, Tanino H, Abo M, Kunakai S and Banks SA: Effect of acetabular component anteversion on dislocation mechanisms in total hip arthroplasty. J Biomech (2011) 44: 1810–1813.
3. Clarke SG, Phillips AT, Bull AM and Cobb JP: A hierarchy of computationally derived surgical and patient influences on metal on metal press-fit acetabular cup failure. J Biomech (2012) 45: 1698–1704.
4. Havelin LI, Engesaeter LB, Espehaug B, Furnes O, Lie SA and Vollset SE: The Norwegian Arthroplasty Register: 11 years and 73,000 arthroplasties. Acta Orthop Scand (2000) 71: 337–353.
5. Fitzgerald RH, Jr., Brindley GW and Kavanagh BF: The uncemented total hip arthroplasty. Intraoperative femoral fractures. Clin Orthop Relat Res (1988): 61–66.
6. Morscher E, Bereiter H and Lampert C: Cementless press-fit cup. Principles, experimental data, and three-year follow-up study. Clin Orthop Relat Res (1989): 12–20.
7. Pilliar RM, Lee JM and Maniatopoulos C: Observations on the effect of movement on bone ingrowth into porous-surfaced

implants. Clin Orthop Relat Res (1986): 108–113.

8. Kwong LM, O'Connor DO, Sedlacek RC, Krushell RJ, Maloney WJ and Harris WH: A quantitative in vitro assessment of fit and screw fixation on the stability of a cementless hemispherical acetabular component. J arthroplasty (1994) 9: 163–170.
9. Ries MD, Harbaugh M, Shea J and Lambert R: Effect of cementless acetabular cup geometry on strain distribution and press-fit stability. J Arthroplasty (1997) 12: 207–212.
10. Markel DC, Hora N and Grimm M: Press-fit stability of uncemented hemispheric acetabular components: a comparison of three porous coating systems. Int Orthop (2002) 26: 72–75.
11. Olory B, Havet E, Gabrion A, Vernois J and Mertl P: Comparative in vitro assessment of the primary stability of cementless press-fit acetabular cups. Acta Orthop Belg (2004) 70: 31–37.
12. Kim YS, Callaghan JJ, Ahn PB and Brown TD: Fracture of the acetabulum during insertion of an oversized hemispherical component. J Bone Joint Surg Am (1995) 77: 111–117.
13. Pastrav LC, Jaecques SV, Jonkers I, Perre GV and Mulier M: In vivo evaluation of a vibration analysis technique for the per-operative monitoring of the fixation of hip prostheses. J Orthop Surg Res (2009) 4: 10.
14. Haidukewych GJ, Jacofsky DJ, Hanssen AD and Lewallen DG: Intraoperative fractures of the acetabulum during primary total hip arthroplasty. J Bone Joint Surg Am (2006) 88: 1952–1956.
15. Hasegawa K, Kabata T, Kajino Y, Inoue D and Tsuchiya H: Periprosthetic Occult Fractures of the Acetabulum Occur Frequently During Primary THA. Clin Orthop Relat Res (2017) 475: 484–494.
16. Mathieu V, Michel A, Flouzat Lachaniette CH, Poignard A, Hernigou P, Allain J and Haiat J: Variation of the impact duration during the in vitro insertion of acetabular cup implants. Med Eng Phys (2013) 35: 1558–1563.
17. Small SR, Berend ME, Howard LA, Rogge RD, Buckley CA and Ritter MA: High initial stability in porous titanium acetabular cups: a biomechanical study. J Arthroplasty (2013) 28: 510–516.
18. Michel A, Bosc R, Sailhan F, Vayron R and Haiat G: Ex vivo estimation of cementless acetabular cup stability using an impact hammer. Med Eng Phys (2016) 38: 80–86.
19. Helgason B, Perilli E, Schileo E, Taddei F, Brynjolfsson S and Viceconti M: Mathematical relationships between bone density and mechanical properties: a literature review. Clin Biomechanics (Bristol, Avon) (2008) 23: 135–146.
20. Adler E, Stuchin SA and Kummer FJ: Stability of press-fit acetabular cups. J Arthroplasty (1992) 7: 295–301.
21. Macdonald W, Carlsson LV, Charnley GJ and Jacobsson CM: Press-fit acetabular cup fixation: principles and testing. Proc Inst Mech Eng H (1999) 213: 33–39.
22. Baleani M, Fognani R and Toni A: Initial stability of a cementless acetabular cup design: experimental investigation on the effect of adding fins to the rim of the cup. Artif Organs (2001) 25: 664-669.