Acetabulum Cup Stability in an Early Weight-Bearing Cadaveric Model of Geriatric Posterior Wall Fractures

Meir Marmor, MD, Riley Knox, BS, Adrian Huang, MB, BCh, BAO, and Safa Herfat, PhD

Background: Primary total hip arthroplasty (THA) has been suggested for posterior wall (PW) fractures with unfavorable features in the geriatric population. There is a paucity of studies reporting on postoperative protocols for primary THA after PW fractures. The purpose of this study was to test the biomechanical effect of immediate assisted weight-bearing on acetabulum THA cup fixation in an osteoporotic PW fracture model.

Methods: Computed tomography scans of 18 geriatric PW fractures (mean age, 77 ± 8 years) were used to generate representative PW fracture. This fracture pattern, comprising 50% of the PW and 25% of the acetabulum rim, was then created in 6 female cadaveric pelves. A multihole acetabulum THA cup was implanted with line-to-line reaming and fixed with four 5-mm screws. The pelves were cyclically loaded to up to 1.8× body weight (BW) in the intact form, after fracture creation and fracture fixation. Optical markers were used to determine acceptable cup motion of less than 150 μm.

Results: Five specimens withstood 3.6× BW loading after implantation and before fracture creation. At 1.8× BW load, cup motion was nonfractured: 50 ± 24 μm (range, 5–128 μm), fractured with no fixation: 37 ± 22 μm (range, 8–74 μm), or fractured with fixation: 62 ± 39 μm (range, 5–120 μm) ($P = 0.0097$). Cup motion was <150 μm for all groups.

Conclusion: This study supports the practice of allowing immediate assisted weight-bearing in patients undergoing THA with PW fractures involving up to 50% of the PW and up to 25% of the acetabular rim, with or without fixation of the PW fragment.

Key Words: Acetabulum fractures, geriatric, elderly, osteoporosis, posterior wall, weight-bearing, rehabilitation, biomechanical testing, cadaver

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INTRODUCTION

Acetabulum fractures in elderly patients with osteoporotic bone are becoming more prevalent.[1–3] Isolated posterior wall (PW) fractures are among the most common acetabulum fractures accounting for up to 20% of the cases.[4–8] Fractures of less than 20% of the PW are considered stable and do not require operative management, whereas fractures involving more than 40% of the PW, having an unstable fracture pattern or instability of the hip under anesthesia, are considered for operative management.[9] However, results of both nonoperative and operative fixation of these fractures have not been optimal, with poor outcomes reported up to 30% of the time.[10–13] In elderly patients with isolated PW fractures, 38% experienced marginal impaction and 44% experienced fracture comminution.[9,14] Both of these factors are associated with poor outcome and need for early total hip arthroplasty (THA).[3,7,10,11,15]

Nonoperative management, followed by delayed THA for posttraumatic arthritis, may result in increased surgical time, blood loss, heterotopic ossification, sciatic nerve injury, and dislocation compared with a primary total hip replacement for nontraumatic osteoarthritis.[16] However, PW Open Reduction Internal Fixation (ORIF) may also result in less than optimal outcome. A major issue with ORIF is the prolonged (up to 12 weeks) duration of restricted weight-bearing that is frequently recommended,[17] which may lead to immobilization and risk of deep vein thrombosis, pneumonia, and permanent loss of mobility.[18–20] Furthermore, revision of PW ORIF surgery to a THA may compromise the outcome of a subsequent THA by compromising the blood supply of the acetabulum and by initiating the formation of scar tissue, heterotopic bone, or occult or frank infection.[21]

Primary THA has been suggested for PW fractures with unfavorable features, such as wall comminution, marginal impaction, and femoral head injury.[22–24] Primary THA has the theoretical benefit of reducing the risk of revision surgery and reduced complication rate by allowing earlier weight-bearing.[21–23] However, there is a paucity of studies reporting on postoperative protocols for primary THA after PW fractures. In most reported cases, weight-bearing is initiated at 6 weeks after the surgery, including cases where a press-fit cup was used.[9,21,23,25–28] The purpose of this study was to test the biomechanical effect of immediate assisted (use of walker) weight-bearing on acetabulum THA cup fixation in an osteoporotic PW fracture model. We hypothesized that in the most common PW fracture pattern in the elderly population, a well-fixed acetabulum cup would experience acceptable motion when exposed to simulate immediate assisted weight-bearing with an assistive device, with and without concomitant ORIF of the PW fragment.

METHODS

Determining the Most Common PW Fracture Pattern in the Elderly Population

The fracture model created for this study was based on the analysis of computed tomography (CT) scans of 18 consecutively treated geriatric PW acetabulum fractures (mean age 77 ± 8 years). Institutional review board exemption for reviewing de-identified patient CT scans was obtained. A 3-dimensional model of each involved hemipelvis (created by Mimics v.15; Materialise, Leuven, Belgium) was cropped, and the femoral head was removed to allow visualization of all fracture lines. An image of a left side acetabulum model (Sawbones, Vashon Island, WA) was used as a template image for fracture mapping. Images of the fractured acetabulum were then sized, positioned, and overlaid on the template image using image manipulation software (GIMP 2.8.4; Free Software Foundation, 2013, Boston, MA). The GIMP pencil tool was used to trace the remaining (stable) portion of each fracture. Each tracing was color filled with equal opacity, and all traced fracture patterns were superimposed, creating final "heat maps" of the remaining (stable) acetabulum surface (Fig. 1). The resulting "averaged" fracture fragment communicated with the acetabulum rim at 12 o'clock and 3 o'clock, as seen in a standardized acetabulum view (white arrows in Fig. 1). The exact dimensions of the fractured PW fragment were determined by analyzing the axial CT cuts for percent PW loss (median, 48%; mean, 49% ± 15%; range, 24%–69%). The individual fracture tracings were used to determine the exact loss of acetabulum rim (median, 25%; mean, 30% ± 11%; range, 18%–52%). For simplicity and reproducibility, the fragment size created in our cadaveric model involved 50% of the PW and 25% of the acetabulum rim.

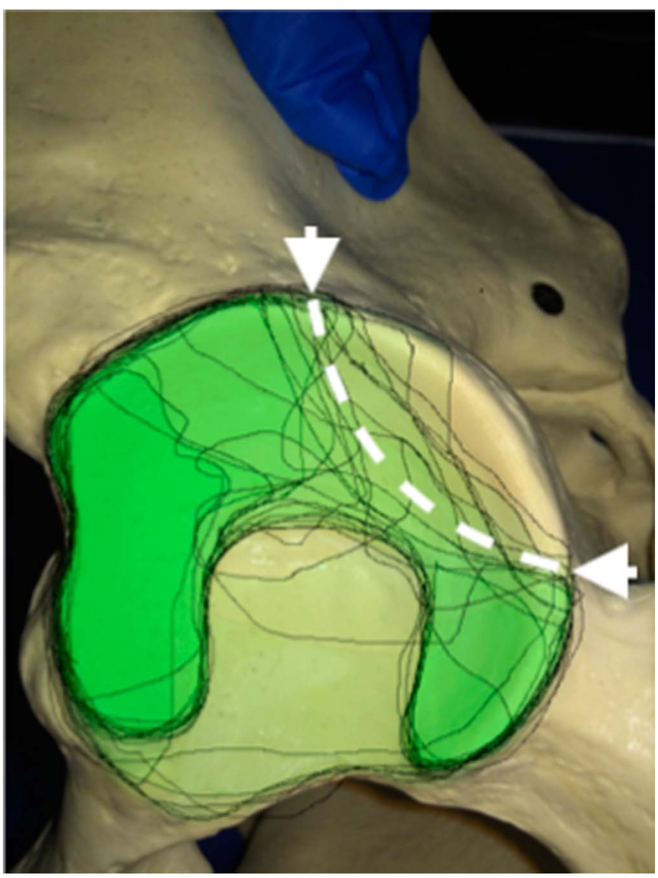

FIGURE 1. CTs of 18 geriatric PW fractures were used to generate a "heat map." The PW fracture model was set to represent the "averaged" PW fracture pattern (white dotted line and rim exit arrows). **Editor's Note**: A color image accompanies the online version of this article.

Mechanical Testing Setup

Biomechanical testing was performed on a servohydraulic material testing machine (Bionix 370 Axial/Torsional; MTS Systems, Corp, Eden Prairie, MN) with a load cell (MC5-2500; AMTI, Berkshire, England) below the base plate. The ilium of each specimen was embedded in potting resin (Smooth-Cast 300; Smooth-On Inc, East Texas, PA) up to an imaginary line connecting the posterior inferior iliac spine and the anterior superior iliac spine. The potted specimen was mounted on sliding tracks, allowing the femoral head to align into the acetabulum throughout the motion (Fig. 2). A femoral stem implant (VerSys Hip System, Zimmer, Warsaw, IN) was embedded in potting resin and attached to the MTS machine actuator for use as a force applicator. The vise pivots were then rotated around the horizontal axes such that a force applied to the acetabular shell implant by the femoral stem applicator was oriented through the sciatic buttress, in a load vector of 12 degrees in the coronal plain and 36 degrees in the axial plane.[29]

Specimen Preparation, Cup Implantation, and Initial Screening

Six paired hemipelvis specimens were obtained from female cadaver pelves (mean age, 81.1 years; range, 61–90 years). Specimens were each implanted with a 50- to 54-mm multihole porous acetabular shell implant (Continuum Acetabular System, Zimmer), based on acetabulum size. Implants were fixed with four 6.5-mm bone screws (Zimmer). Three screws were directed into the sciatic buttress of the ilium; the fourth was directed into the ischium (Fig. 3). A polyethylene liner (Zimmer) was placed inside the shell implant. All specimens were implanted by the same surgeon (M.M.) to minimize interspecimen variability. To assure that our cadaver model was able to withstand the normal acceptable loads for a primary THA, all specimens were first tested in the intact state with the full–weight-bearing loading protocol.

Fracture Creation and Fixation

Following the first round of intact acetabulum testing, PW acetabular fractures were created in each hemipelvis, according to the previously determined most common fracture pattern (see above, Fig. 1). A semicircular path was created between the superior (12 o'clock) and

FIGURE 2. The mechanical testing setup is shown without specimen. **Editor's Note**: A color image accompanies the online version of this article.

posterior (3 o'clock) exit points. Holes were drilled by a surgeon along the length of the path, and the fracture was completed using an osteotome. The fragment involved 50% of the acetabulum wall width and comprised 25% of the acetabulum rim. Following fracture creation, one fragment was fixed with an 8-hole 3.5-mm buttress plate (Synthes, West Chester, PA) using 2 proximal and 2 distal 3.5-mm cortical screws (Synthes) for fixation (Fig. 4). The paired fragment (from a similar fracture created in the contralateral hemi pelvis) was removed and left unfixed.

Optical Tracking System Setup

In addition to the MTS measurements, optical measurement sensors (OptoTrak Certus; Northern Digital Inc, Waterloo, Canada) were attached to the specimen to track implant motion relative to the bone. Unpublished static data from our laboratory indicated that the distance measurements acquired by the optical sensors have less than 10-μm error. This measurement validation was performed with the optical markers attached to a micrometer with single micrometer accuracy. Two marker sets were attached to the femoral stem potting fixture; the distance between these marker sets was used to quantify noise in other measurements due to the motion of the MTS system. Two additional marker sets were secured to the bone using pins; the distance between these marker sets was used to detect and quantify gross bone movement. A fifth and final marker set was secured to the polyethylene implant liner; the distance between this marker set and a set secured to the bone was used to measure implant motion relative to the bone (Fig. 5).

Data Acquisition and Analysis

Axial displacement, axial force, and running time were recorded by the MTS controller at a rate of 102.4 Hz. Optical tracking data were recorded at 100 Hz. Following the completion of both tests, cup motion data were calculated for each 1 Hz loading interval. Single-factor analysis of variance ($\alpha = 0.05$) was used to compare the 3 study groups (nonfractured, fractured with fixation, and fractured without fixation). Implantation failure was defined as cup motion greater than 150 μm.[30,31] Previous studies in dogs[30] and human autopsies[31] have shown that fibrous tissue attachment rather than bone ingrowth occurred when relative motion between the bone and the implant exceeded 150 μm. Cup motion data were examined to identify any optical measurement intervals where this value was exceeded.

Mechanical Testing Protocol

The mechanical testing protocol was set to simulate the first 2 weeks of assisted ambulation after THA. During this period, it is unlikely for enough bone ingrowth to occur and add to the stability of the cup.[32]

Before fracture creation, specimens were mechanically tested to assess the quality of the implant procedure and ensure that specimens would not fail prematurely. Unfractured specimens underwent a full–weight-bearing loading protocol (as would be allowed after a standard primary THA) as described below:

1. 10-second static hold at 100 N
2. Cyclic compressive loading between 100 N and 1.2 times body weight (BW) for 5000 cycles at 3 Hz
3. After initial static hold and after every 1000 cycles, the specimen was loaded at 1 Hz for 10 cycles as optical tracking data were recorded
4. Following initial 5000 cycles, the upper cyclic limit was increased 0.6 times BW every 5000 cycles until 3.6 times BW was achieved, culminating in a total of 25000 cycles.

Following initial testing and fracture creation, specimens underwent the following loading protocol to simulate assisted weight-bearing:

1. 10-second static hold at 100 N
2. Cyclic compressive loading between 100 N and 1.2 times BW for 2000 cycles at 3 Hz
3. After initial static hold and after every 2000 cycles, the specimen was loaded at 1 Hz for 10 cycles as optical tracking data were recorded
4. Following the initial 10,000 cycles, the upper cyclic limit was increased to 1.8 times BW. The 10,000-cycle loading interval was repeated and optical measurement data were recorded in the same fashion. 20,000 cycles were performed in total.

The upper loading limit of 1.8 times BW is consistent with the results of Damm et al,[33] who demonstrated peak hip

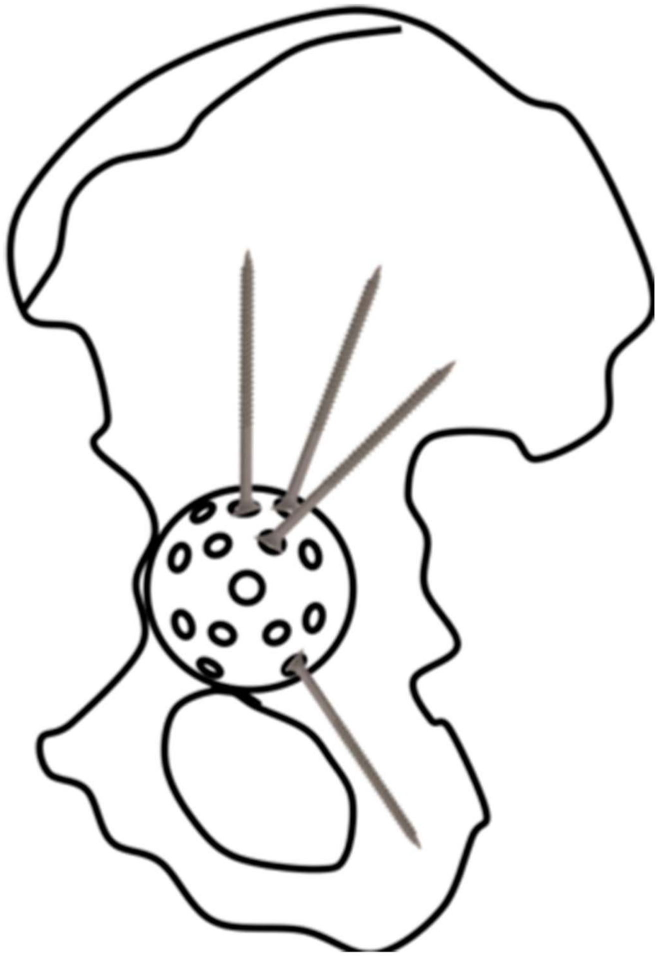

FIGURE 3. Acetabular shell implant and screw fixation pattern and trajectories. **Editor's Note**: A color image accompanies the online version of this article.

joint resultant forces to be approximately 1.8 times BW during assisted (use of walker) walking.

RESULTS

Tracing and overlapping the available CT scans of geriatric PW fracture yielded the "heat map" shown in Figure 1. The derived "averaged" PW fracture fragment exited the acetabulum rim at 12 o'clock and 3 o'clock (white arrows), comprised 25% of the rim and was 50% of the size (depth) of the wall at the level of the fracture (dotted line).

All specimens withstood 3.6 × BW loading after implantation and before fracture creation, without failure of fixation, recording cup motion of 115 ± 121 μm. One of the specimens recorded a cup motion of 334 ± 149 μm (range, 167–526 μm) and was therefore excluded from final analysis. After exclusion, average cup motion of the remaining 5 specimens was 72 ± 42 μm (range, 7–161 μm). At 1.2 × BW, all 3 study groups showed very similar levels of average cup motion: nonfractured 38 ± 30 μm (range, 4–149 μm); fractured with no fixation: 27 ± 18 μm (range, 0–54 μm); fractured with fixation: 40 ± 23 μm (range, 5–86 μm). There was no statistically significant difference in cup motion between any of the 3 groups at this load interval ($P = 0.127$). At 1.8 times BW load, cup motion was nonfractured: 50 ± 24 μm (range, 5–128 μm); fractured with no fixation 37 ± 22 μm (range, 8–74 μm); fractured with fixation: 62 ± 39 μm (range, 5–120 μm) ($P = 0.0097$). Cup motion was <150 μm for all groups (see **Figure**, **Supplemental Digital Content 1**, http://links.lww.com/JOT/A837).

FIGURE 4. Positioning and fixation of fragment buttress plate. **Editor's Note**: A color image accompanies the online version of this article.

DISCUSSION

The findings of this study support our hypothesis that immediate assisted weight-bearing after primary THA in the setting of a PW acetabulum fracture may be possible. This preliminary study also did not demonstrate a clear benefit of fixation of a PW fracture fragment such as the one used in our model.

Surgical management for PW acetabulum fractures is recommended when the hip is unstable or incongruent.[34] CT scans have been suggested as radiographic method for the assessment of stability, with a wall fragment size greater than 40%–50% considered unstable, less than 20% considered stable, and 20%–40% considered indeterminant[34–36] More recent studies have suggested that the location of the PW fragment relative to the acetabulum dome may be more important to hip stability than its size.[37,38] To our knowledge, this is the first study to assess stability of an acetabulum cup

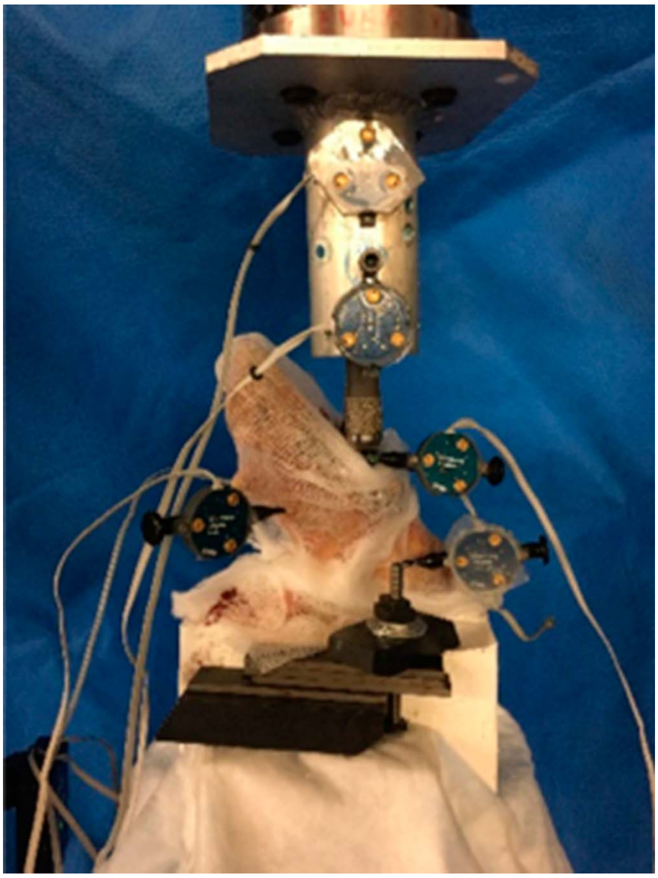

FIGURE 5. Specimen with attached optical measurement marker sets. **Editor's Note**: A color image accompanies the online version of this article.

implant, rather than the native hip, in the presence of an PW acetabulum fracture. The PW fracture model that we created involved 50% of the acetabulum wall and therefore would have been considered an indication for surgery in a clinical setting. We additionally sized the fracture to include 25% of the acetabulum rim or circumference. We are also unaware of any previous studies that have measured this parameter in relation to hip stability. To assure clinical relevance of our model, the chosen size for the PW fragment was based on serial tracings of clinical cases of PW fractures in elderly patients. The creation of a "heat map" of this fractures resulted in the selected size and location of the PW fragment used in the model.

Primary THA for PW fractures has been reported in a number of clinical series.[4,23,39,40] In a clinical series reporting on ORIF in combination with primary THA for 9 isolated PW fractures, ORIF was performed in all cases before implanting the acetabular component.[39] In all cases, the acetabular subchondral bone was preserved. The acetabulum was underreamed by 1 mm, and a press-fit cup was inserted. The femoral head was morselized and used as autograft in most cases, and the cup was anchored using 2, 3, or 4 screws. Constrained liners were avoided. Patients were kept touchdown weight-bearing for 8 weeks and partial weight-bearing over the next 4 weeks. The acetabular cup showed an average medial displacement of 1.2 mm (range, 0–3 mm) and an average vertical displacement of 1.3 mm (range, 0–4 mm), but there was no radiographic evidence loosening of the acetabular component in an average follow-up of 3.9 years (range, 1–10.1 years).[39] We did not encounter any permanent displacement of the acetabulum cup in our study. This fact may be due to the preloading of the specimens before the optimetric motion testing that allowed the cups to settle in their final position before motion measurements and due to the fixation of the cup with 4 screws in all specimens. Other reports on primary THA for PW fractures recommended 6 weeks of touchdown or non–weight-bearing after surgery.[4,23] In this study, we did not encounter failures (ie, cup motion that exceeds the recommended motion for bone ingrowth) in all 5 pelves that were included in our final analysis. Therefore, the findings of the current study support an immediate or early weight-bearing protocol in similarly sized PW fragments, especially if the PW fragment undergoes ORIF before cup implantation. In a more recent clinical series of elderly patients (mean age, 77 years; range, 63–90 years) with various acetabulum fracture patterns including isolated PW or associated patterns with PW involvement, they were allowed immediate weight-bearing. In this series, no component migration was seen in an average follow-up of 24 months (range, 8–38 months).[40] Three or 4 screws were used to fix the acetabulum cup in most cases, similar to our current study, which used 4 screws.

In the setting of revision THA surgery, it is generally accepted that implantation of a noncemented cup without augmentation is possible for bony defects that are less than 50% of the acetabulum rim.[41–43] Such implantations are followed by protected weight-bearing protocols.[43] The typical PW fracture pattern that is encountered in the elderly population is different in size and position compared with the bone loss encountered in revision THA and may justify separate consideration when devising cup fixation and rehabilitation protocols. In our preliminary review of CT scans of elderly patients with PW fractures, we found that the typical PW fragment comprised about 25% of the acetabulum rim and was located at the superior–posterior (12–3 o'clock) position adjacent to the sciatic buttress (Fig. 1). This is in contrast to the more superior (9–3 o'clock) bone defect described in revision THA surgery.[43] This study demonstrated adequate cup stability with or without fixation of the PW fragment. These findings support a more liberal weight-bearing protocol for PW fractures as compared with the acetabulum rim deficiencies encountered in revision hip arthroplasty surgeries.

Some limitations of this study include the difficulty in applying the results to different fracture patterns, and to different weight-bearing protocols. Although bigger fracture PW fragments than was modeled in this study can be encountered in the clinical setting, the modeled PW fragment was 50% of the PW size, making it a surgical indication to prevent hip instability and was an "averaged" representation of 18 consecutively encountered geriatric PW fractures, making it clinically relevant. Furthermore, in this study, the cups were inserted with line-to-line reaming and fixed with 4 screws. The effect of press fitting the cup and perhaps using fewer screws was not examined. The purpose of this study was to demonstrate at least 1 type of implantation strategy that may allow early weight-bearing. Future studies can address other implantation strategies. Finally, the same specimens were loaded twice, once as an intact acetabulum with a cup implanted line to line with 4 screws and then again after fracture fixation. The biomechanical properties of the construct may have changed due to bone impaction and cup settling after the first loading. Fracture creation seemed to increase cup motion after fixation and decrease cup motion without fixation. However, these differences were within the 10-μm error of measurement and were statistically insignificant. Furthermore, we feel that this first step was necessary to assure the quality of our bone model and to establish proper control.

In summary, the findings of this study support the practice of allowing immediate assisted weight-bearing for geriatric patients, in the setting of primary THA, with up to 50% PW fracture size, involving up to 25% of the acetabulum rim. We were not able to demonstrate that fragment fixation contributed to cup stability. Clinical series with more liberal weight-bearing protocols are needed to determine the influence of immediate weight-bearing on patient outcome in this population.

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