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Biomechanical Consequences of Fracture and Repair of the Posterior Wall of the Acetabulum*

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INVESTIGATION PERFORMED AT THE DEPARTMENT OF ORTHOPAEDIC SURGERY, UNIVERSITY OF CALIFORNIA DAVIS MEDICAL CENTER, SACRAMENTO, CALIFORNIA

ABSTRACT: We measured the distribution of contact area and pressure between the acetabulum and the femoral head of cadaveric pelves in three different conditions: intact, with an operatively created fracture of the posterior wall, and after anatomical reduction and fixation of the fracture with a buttress plate and screws. The study involved eight cadaveric hip joints from five pelves loaded to 2000 newtons in simulated single-limb stance. Measurements were made with pressure-sensitive film. The acetabulum was divided into three areas — the anterior wall, the superior aspect, and the posterior wall — for the analysis of the data.

The creation of a fracture of the posterior wall was followed by an increase in contact area, maximum pressure, and contact force in the superior aspect of the acetabulum. A concomitant decrease in these parameters was observed in the anterior and posterior walls. Anatomical reduction and fixation of the fracture with a plate and screws did not restore the pattern of loading to pre-injury levels.

CLINICAL RELEVANCE: This study demonstrates the marked alteration in the mechanics of load transmission across the hip after a fracture of the posterior wall of the acetabulum. These findings are consistent with the clinical observations of Rowe and Lowell that large fractures of the posterior wall of the acetabulum that have been treated non-operatively predispose the hip joint to osteoarthritis. The failure of acute anatomical reduction and internal fixation to restore normal joint-loading parameters supports the current clinical practice of restricting weight-bearing after operative repair of these fractures.

The recognition that osteoarthritis may be a late sequela of a poorly reduced acetabular fracture has led to the practice of open reduction and internal fixation of these fractures. The primary indications for operative treatment of fractures of the posterior wall include instability of the hip, incarcerated or impacted osteochondral fragments, and an irreducible fracture-dislocation of the hip. The philosophy guiding this intervention is that restoration of normal anatomy should preserve function of the joint and thereby prevent later degenerative changes that culminate in osteoarthritis. However, post-traumatic osteoarthritis of the hip joint has been reported in association with as many as 20 per cent of fractures of the posterior wall of the acetabulum after treatment with open reduction and internal fixation. Letournel and Judet as well as Letournel and Matta noted that comminution of the fragment of the posterior wall is a predictor of a poor outcome. Rowe and Lowell observed that posterior instability after repair of these fractures is an additional predictor of osteoarthrotic sequelae. We investigated the mechanical basis of these poor clinical outcomes, which, to our knowledge, have not been previously subjected to biomechanical study. To test the hypothesis that operative reduction and internal fixation of a fracture of the posterior wall of the acetabulum will restore normal mechanical function to the joint immediately, we examined the mechanics of load transfer on intact, fractured, and repaired cadaveric acetabula.

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Illustration of the jig used to position the pelvis and femur. The pelvis is attached to an angled mounting block with a one-half-inch (1.27-centimeter) diameter bolt through the sacral body. Rods through the sacral alae, and supporting the posterior superior iliac spine, prevent rotation about the bolt when the hip joint is loaded. The femoral shaft is fixed in an aluminum tube with polymethylmethacrylate. 

perpendicular to the end plate of the first sacral vertebra, provided primary attachment of the pelvis to the upper portion of the loading jig. Secondary attachments counteracted the moment produced about the bolt by the joint-reaction force. Eight-millimeter-long rods through the sacral alae prevented rotation of the sacral body. An additional rod with a u-shaped fitting over the posterior superior iliac spine prevented excessive motion of the sacro-iliac joint.

The pelvis was mounted with the plane formed by the anterior superior iliac spine and the pubic symphysis aligned vertically. The relative position of the pelvis and femur during testing was selected on the basis of the work of McLeish and Charnley. In the frontal plane, the femoral shaft was placed in 15 degrees of adduction relative to the pelvis; in the sagittal plane, the femoral shaft was vertical. The femur was oriented in 5 to 10 degrees of internal rotation, although the exact amount of internal rotation was difficult to determine because the femoral shafts had been transected at the time of harvest. The orientation of the joint-reaction force vector was 25 degrees medially inclined from the femoral shaft in the frontal plane and parallel to the femoral shaft in the sagittal plane. The proximal aspect of the femur and the pelvis were rotated as a unit to align the joint-reaction force vector with the loading axis of the materials-testing system. The specimens were initially mounted with the joint capsule intact. The loading jig was marked to allow the specimen to be returned to the proper position after disarticulation, and the entire capsule and its insertion into the labrum were removed.

Before loading, 2.0-millimeter holes were drilled through the articular cartilage and the underlying bone of the acetabulum at points 30 degrees on either side of the acetabular vertex and midway between the acetabular fossa and rim. During loading, a blunt probe was used to mark the pressure-sensitive film (low-range Fuji Prescale Film: C. Itoh, New York, N.Y.) through these holes to establish orientation of the film with respect to the acetabulum. The outline of the acetabular rim was also marked on the film. The specimens were kept moist throughout testing with normal saline solution at room temperature. The specimens were loaded at twenty millimeters per minute to 2000 newtons for each of three conditions: with the acetabulum intact, with a simulated fracture of the posterior wall (with the fragment removed), and after reduction and internal fixation of the fragment. These three conditions will subsequently be referred to as intact, fractured, and repaired. Loads were maintained for thirty seconds. Two loading cycles were conducted for each test condition.

The simulated fracture of the posterior wall began at 40 degrees posterior to the acetabular vertex along

Fig. 2
Illustration of the simulated fracture of the posterior wall of the acetabulum. The fracture began 40 degrees posterior to the acetabular vertex and extended another 50 degrees. The simulated fracture created a defect of the entire width of the articular surface of the posterior wall with this 50-degree arc. The inferior portion of the articular surface of the posterior wall (the ischial facet) remained intact.
Illustration of the repair of the fracture with interfragmentary screws and a 3.5-millimeter seven-hole small-fragment reconstruction plate used in a buttress configuration. The reduction was determined to be anatomical both visually and by digital palpation of the articular surface.

The rim of the acetabulum (Fig. 2) and continued along the arc of the posterior rim to 90 degrees posterior to the vertex. The fragment extended medially to include 50 per cent of the width of the retroacetabular surface, as measured from the posterior acetabular rim to the greater sciatic notch, and the entire width of the articular surface throughout the 50-degree arc was removed. The inferior portion of the posterior articular surface, which we refer to as the ischial facet, remained intact. The fracture of the posterior wall was made with the use of holes drilled to the subchondral bone but not through the articular cartilage. The drill-holes were connected with an osteotome to create a realistic fracture in the articular surface.

The fracture was subsequently repaired by one of us (S. A. O.), an experienced surgeon, under ideal benchtop conditions with excellent access and visibility. A 3.5-millimeter seven-hole small-fragment reconstruction plate (Synthes U.S.A., Paoli, Pennsylvania) used in a buttress configuration and small-fragment screws were employed for internal fixation of the fragment of the posterior wall. Two bicortical screws were inserted proximal and distal to the fragment, and two interfragmentary screws were inserted through the posterior part of the fragment but outside the plate (Fig. 3). The articular surface was assessed visually and with digital palpation at the time of the reduction. All reductions were anatomical. There was no articular step-off; however, there were slight gaps (less than one millimeter wide) between the articular margins of the fragment and the remaining surface of the joint.

Pressure patterns were recorded with the Fuji film\textsuperscript{22,23}. This low-range film, which is sensitive to pressures between 2.5 and 10.0 megapascals, was selected on the basis of previous reports of hip-joint contact pressures\textsuperscript{3}. The film was cut into ellipses of 1.0 x 8.0 centimeters that were tacked to the surface of the femoral head with a photographic mounting adhesive. Before the film was applied, the head of the femur was covered with a thin layer of latex (Trojan Latex Condom: Carter Wallace, New York, N.Y.) to protect the film from the moisture on the articular surface. Eight strips of film were applied to each femoral head for each measurement. The first strip was located over the vertex in the axis of the femoral neck beginning at the fovea. Three pieces were placed anterior to the first strip, and four pieces were placed posterior to it. A second layer of latex was then placed over the film. The resting thickness of the latex-film-latex layer was 300 micrometers. This thickness decreased to 250 micrometers under the compressive load of 2000 newtons.

After loading, the strips of pressure-sensitive film were removed from the femoral head, carefully aligned on three by five-inch (7.6 by 12.7-centimeter) cards, and laminated in plastic to facilitate handling. All films were analyzed with a three-stage process of digitizing, filtering, and measurement. Digitizing was conducted with a flatbed scanner (Abaton Scan 300/GS: Everex Systems, Fremont, California) at a spatial resolution of 2.95 pixels per millimeter and 256 levels of gray. Contrast and brightness controls were set to give a continuous histogram covering the entire range of the film. Filtering and measurement were conducted with Image software (Wayne Rasband, Research Services Branch, National Institute of Mental Health, Bethesda, Maryland) on a Macintosh IIcx computer (Apple Computer, Cupertino, California). We produced a calibration curve by applying known pressures to the latex-film-latex constructs with a small Delrin cylinder (DuPont, Wilmington, Delaware). This curve agreed well with the low-humidity calibration curve supplied by the film manufacturer (Fig. 4). Since our curve reflected our test conditions...
TABLE I

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Index of Singh et al.</th>
<th>Osteoarthrosis Score</th>
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<td>2.38 3.23 6.23</td>
<td>0.89 3.03 4.37</td>
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</tbody>
</table>

(rate of loading, duration of application of the load, latex barriers, and humidity and temperature in the laboratory), it was used for all measurements.

Two digital filters were used to prepare the images for measurement. A background-subtraction filter was used first to reduce the effects of slight variations in scanning brightness, and then a convolution filter was applied to smooth the film signal spatially. The microcapsule basis of the film produces a grainy image, particularly under the low-humidity conditions (35 percent relative humidity) of our laboratory. The manufacturer’s instructions recommend averaging measurements of film density over an area of at least 2.0 square millimeters to prevent the grain of the image from adversely influencing the pressure readings. Convolution filtering conducts this averaging function in a single operation for the entire film image. With a pixel area of 0.124 square millimeter, the smallest convolution kernel that covers at least 2.0 square millimeters is five by five pixels. We used a slightly larger (seven-by-seven pixel) filter with a gaussian weighting profile to achieve a similar degree of smoothing with less peak broadening. Only signal intensities of more than 2.5 megapascals were included in the measurements, as this is the lower limit of reliability for the film used.

Two separate film patterns were recorded for each hip in each experimental condition. The repeat patterns were evaluated qualitatively for consistency at the time of the test; any pairs that had obvious disagreement were rejected and the test was repeated. All measurements represent the mean of the two accepted repeat patterns.

The images were divided into three regions — the anterior wall, the superior aspect, and the posterior wall of the acetabulum — on the basis of the reference marks established during testing. This division separated the acetabulum approximately into thirds. The contact area and maximum pressure were measured within each region. The mean pressure was calculated as the mean pixel density converted to pressure units with the calibration curve. Pressure was integrated over the contact area of each region to give the resultant contact force directed perpendicular to the surface of the joint. Joint-reaction force was calculated as the sum of the vertical component of contact force for the entire joint. Parameters within each region of the acetabulum were analyzed by single-factor repeated-measures analysis of variance (the factor was the condition and the levels were intact, fractured, and repaired) and Dunnett multiple-range follow-up tests. P values of less than 0.05 were considered significant. The results are given as the mean and standard deviation for each condition.

Two analyses were conducted to evaluate the reliability of the pressure measurements. First, five repeat
loadings to 2000 newtons were conducted for a single hip joint in the intact state. The coefficients of variation for pressure and contact area were calculated. Second, the joint-reaction force calculated from the pressure pattern was compared with the 2000-newton applied load to verify the fidelity of load recovery.

Results

Two hip joints (from two cadaveras) had gross evidence of degenerative disease and were not tested. The statistical analyses are based on data from the remaining eight samples (Table 1). The five repeat loadings of a single intact hip joint produced coefficients of variation of 0.06, 0.08, and 0.20 for mean pressure, maximum pressure, and contact area, respectively. The relatively large variance for contact area was primarily caused by one spurious measurement. Deletion of this value reduced the coefficient of variation to 0.08. We found the two patterns that were observed during testing to be consistent within our qualitative judgment for all specimens, and no tests were repeated. The joint-reaction forces calculated from the pressure patterns were 2080 ± 426, 1840 ± 490, and 1700 ± 464 newtons for the intact, fractured, and repaired conditions, respectively. With the numbers available, there were no significant differences among these groups (p = 0.27).

Contact Area

The mean total contact area for the intact acetabulum was 6.84 ± 1.74 square centimeters. The distribution of contact area was approximately equal among the posterior, superior, and anterior regions (2.40 ± 0.78, 1.60 ± 0.74, and 2.84 ± 0.74, respectively). After the fracture, there was a significant decrease (p < 0.05) in the contact area on the anterior and posterior walls and a nearly significant increase (p = 0.07) in the superior aspect of the acetabulum. After the repair, the contact area on the anterior and posterior walls remained significantly decreased and the total articular contact of the hip joint was significantly decreased (p < 0.05).
The maximum contact pressure. Each region of the acetabulum supported approximately equal maximum pressure in the intact state. There was significantly greater \((p < 0.05)\) maximum pressure on the superior aspect of the acetabulum in the fractured and repaired conditions.

The contact force. The regional distribution is similar to that for the contact area. The force is even across the joint in the intact state, and it is increased on the superior aspect of the acetabulum and is decreased on the anterior and posterior walls after the fracture. Reverses in these changes after the fracture was repaired were not significant.

The mean contact area decreased to 1.29 ± 0.45 square centimeters on the posterior wall and to 0.64 ± 0.48 square centimeter on the anterior wall. Both changes were significant \((p < 0.01)\) and were concomitant with an apparent increase in the contact area on the superior aspect of the acetabulum to 3.36 ± 1.11 square centimeters, although this change was just short of being significant \((p = 0.07)\).

Anatomical reduction and fixation of the fragment of the posterior wall did not restore the total contact area or the distribution of contact within the acetabulum to that of the intact condition. The mean contact areas for the total joint and the posterior and anterior walls remained significantly less \((p < 0.01)\) than the values for the intact acetabulum. The mean contact area on the superior aspect of the acetabulum remained increased but was not significantly different from that for the intact state. There were no significant differences in the contact area between the repaired and fractured conditions.

**Contact Pressure**

There were slight but significant changes in the mean and maximum pressures in the superior aspect of the acetabulum in response to the fracture of the posterior wall of the acetabulum (Figs. 6 and 7). The mean pressure increased from 3.51 ± 0.48 to 4.14 ± 0.51 megapascals \((p = 0.01)\), and the mean maximum pressure increased from 5.83 ± 1.16 to 7.45 ± 1.00 megapascals \((p = 0.01)\). The mean and maximum pressures on the posterior and anterior walls showed no significant changes.

Reduction and fixation of the fragment did little to reverse the changes in pressure caused by the simulated fracture. The mean pressure on the superior aspect of the acetabulum remained significantly higher than that
for the intact condition (p = 0.03). The maximum pressure showed a similar trend. The pressure on the anterior and posterior walls did not change significantly with fixation of the fracture.

Contact Force

The mean contact force had a pattern that was similar to that of the contact area (Fig. 8). In the intact acetabulum, each of the three regions supported approximately equal levels of contact force (889 ± 354 newtons for the posterior wall, 788 ± 351 newtons for the superior aspect, and 806 ± 292 newtons for the anterior wall). After the fracture had been created, the contact force on the superior aspect of the acetabulum increased to 1403 ± 530 newtons (p = 0.01). There were significant decreases (p < 0.01) in the contact force on the anterior and posterior walls.

After the fracture had been repaired, the contact force on the superior aspect of the acetabulum decreased to 1114 ± 567 newtons. This value was between those for the intact and fractured conditions and was not significantly different from either one. The mean contact force on the anterior and posterior walls remained significantly lower (p < 0.01) than the values for the intact acetabulum. There were no significant differences between the repaired and fractured states in any region of the acetabulum.

Discussion

The results of this study demonstrate that fractures of the posterior wall of the acetabulum significantly alter the patterns of loading and contact pressure in the hip joint during single-limb stance. After the fracture, the total articular contact area was decreased by 1.56 square centimeters. Within the acetabulum, the contact area was simultaneously decreased on the anterior wall (by 1.54 square centimeters) and the posterior wall (by 1.11 square centimeters) and was increased on the superior aspect of the acetabulum (by 1.09 square centimeters). The mean and maximum pressures on the superior aspect of the acetabulum increased as well. Despite an anatomical reduction and good fixation, the repair did not significantly improve the altered loading pattern seen in the fractured state. Clinically, these fractures are often comminuted and thus acute repairs would be expected to result in even less mechanical integrity than in this bench-top study.

Our interpretation of the changes in the mechanics of the hip joint after a fracture and the failure of anatomical operative repair to restore normal loading is based on the concept of the hip as an incongruous joint in which the femoral head is somewhat larger in diameter than the unloaded acetabulum. The joint then becomes, as described by Bullough et al., “a ball thrust into a Gothic arch.” In this paradigm, the contact at low loads is anterior and posterior, with the superior region unloaded. At loads of more than approximately one-quarter to one-half body weight, the femoral head makes contact with the superior portion of the acetabulum. At higher loads, such as those that occur during walking, the contact and pressure are spread evenly over the surface of the acetabulum by a combination of bone and cartilage deformation. During this process, the femoral head expands the joint by forcing the anterior and posterior walls apart, and peripheral contact pressures result.

Consistent with this interpretation, we observed an even distribution of all parameters (contact area, mean and maximum pressure, and contact force) in the intact joint at a load of 2000 newtons and a clear decrease in peripheral contact after simulated fracture of the posterior wall. With the circumferential congruity of the acetabulum disrupted, there is little resistance to expansion and the femoral head makes superior contact without the development of normal peripheral contact force. Decreased peripheral contact also explains the increase in contact force within the superior aspect of the acetabulum of the fractured joint. Even though contact force is directed toward the center of the joint (in the absence of friction), any vertical component of this force contributes to the resolved joint-reaction force vector. When the portion of the vertical reaction force that is normally supplied by peripheral contact is missing, the superior contact force must increase to make up the difference. Failure of fixation to restore normal mechanics of the joint indicates inadequate stiffness of, or inadequate load transfer to, the reconstruction hardware. Given the stiffness of the reconstruction hardware, the most likely possibility is compromise of load transfer due to motion at the screw-plate and screw-bone interfaces.

The experimental protocol used in this study has several advantages compared with previous biomechanical studies of normal hip joints. By leaving the pelvic ring intact for mechanical testing, more normal deformations of the acetabulum can be expected with loading than would be the case when the ilium is rigidly embedded in plastic. Because the femur and pelvis are mounted and aligned with the ligamentous structures and capsule intact, anatomical positioning can be ensured. Thereafter, the specimen can be returned repeatedly to this alignment even after the joint has been disarticulated. The jigs also allow precise regulation of the direction and magnitude of the joint-reaction force vector. We chose to investigate a position that simulates the single-limb stance phase of gait. This position is one in which the hip sustains large loads, and it has been widely used in other studies. Other activities, such as rising from a chair or descending stairs, may cause greater forces on the posterior wall, but they have not been as well characterized as single-limb stance.

The fracture created in these specimens left the inferiormost portion of the posterior wall intact. The accompanying articulation, the ischial facet, also re-
BIOMECHANICAL CONSEQUENCES OF FRACTURE AND REPAIR OF THE POSTERIOR WALL

The advantage of pressure-sensitive film is that it can be used to measure joint-contact areas and pressures simultaneously. Other methods that have been employed in investigations of the hip joint can be used to measure contact area but not pressure (dye studies and castings) or to measure pressure locally but not globally (piezoelectric transducers and mechanical transducers). Fuji film, however, is not free of technical problems. The dye transfer basis of the film and the need to digitize and process image data can lead to measurements that are more variable than those made with transducer-based techniques. The latex-film-latex barrier is 250 micrometers thick when loaded at 2000 newtons, and it therefore increases the diameter of the femoral head, in turn altering the head-acetabulum geometric relationship. Pressures measured are in a range, not continuously, to a maximum limiting value. Low-range film, for example, is most accurate between 2.5 and 10.0 megapascals. By thresholding, we specifically excluded any signal of less than 2.5 megapascals. Accurate measurements also require application and maintenance of load during a period of time that is substantially longer than the stance phase of gait. Creep deformation of cartilage during the loading period could alter the area and pressure measurements made by the film.

We conducted five repeat loadings of a single intact hip joint in order to assess the variability associated with our film-analysis technique directly. The coefficients of variation for area and pressure parameters among the first four measurements were between 0.06 and 0.08, a finding that agrees with the 6 per cent variability reported in a previous study in which Fuji film was used for measurements in the hip joint. The fifth measurement yielded a spurious value for contact area, increasing the coefficient of variation for this parameter to 0.20. On the basis of this experience and practical considerations in conducting the experiment, we established the protocol of making two measurements for each condition. Thus, when a film imprint had obvious irregularities, the measurement could be repeated.

Problems associated with the thickness of the film and the low pressure threshold can be analyzed by comparison of the applied load with the joint-reaction force calculated from the pressure pattern on the film. Brown and Shaw, for example, noted a 12.9 per cent discrepancy between applied and calculated loads in a study in which they used pressure transducers. We measured a joint-reaction force that was approximately equal to the applied load in the intact joint and was 200 to 300 newtons less in the fractured and repaired conditions. Since our measurements did not include pressures of less than 2.5 megapascals, a value that was less than the applied load was expected. The values for the fractured and repaired conditions were consistent with this expectation, but the value for the intact condition was not. We interpret the extra load in the intact joint as an artefact associated with the thickness of the film. The differences between the joint-reaction-force values, however, do not approach significance (p = 0.27), whereas many changes in loading parameters within the joint were significant (p < 0.05). In addition, there was no recovery of this extra load with fixation of the joint. We are confident, therefore, that our interpretation of changes associated with fracture and repair are reliable.

It is more difficult to interpret the mechanics of a normal joint with a thickness artefact present. The incongruous joint model provides the best explanation of our findings, but the film-and-latex construct increased the radius of the femoral head by approximately 1 per cent. It is uncertain to what extent this exaggerated peripheral loading. The incongruous hip-joint model is controversial. Evidence supporting this concept comes from dye contact studies, casting studies, measurements of periacetabular strain, and distribution patterns of osteoarthritic lesions. Hammond and Charnley and Brown and Shaw, however, failed to observe early peripheral contact. Greenwald and O'Connor noted that incongruous hip joints were typical in younger individuals and that the incongruity had been lost in cadaveric specimens from individuals who had been elderly at the time of death. Variations in the ages of individuals from whom the specimens had been obtained after death may thus account for some of the inconsistencies in the evidence for incongruity. We believe that, over-all, the evidence for an incongruous joint is strong.

There is creep of the cartilage and subchondral bone during the test, although the exact extent is difficult to evaluate. The expected results of creep, however, do not weaken our conclusions about the changes associated with a fracture and repair. Compression of cartilage would act to produce a more even distribution of pressure within the joint than that in the instantaneous-load state. Within the context of our analysis, this is a conservative error. It would tend to produce differences in contact area and pressure that are less, not more, than the instantaneous-load values. A more sophisticated method of measurement of pressure is needed to address this issue fully.

The long-term clinical implications of our observations are unclear because we observed only the acute situation and not the effects of fracture-healing. Hadley...
et al. observed that increased pressure in the hip, when maintained for a period of years, was prognostic for degenerative changes\(^{11}\). We observed increases of 0.63 megapascal in mean pressure and 1.62 megapascals in maximum pressure on the superior aspect of the acetabulum after a fracture of the posterior wall. Failure to repair or inaccurate reduction of such a fracture might lead to later degenerative changes, as has been shown in previous clinical studies\(^{16,18,21,27-29}\). The satisfactory long-term results after anatomical repair demonstrated by some of these authors\(^{21,22,25}\) suggest that healing of the fracture may restore the mechanics of the joint. Despite this possibility, our findings underscore the importance of limited weight-bearing in the early period after operative repair. Until the fracture has healed, it must be assumed that the mechanics of the joint are abnormal even when an anatomical reduction has been reinforced with a buttress plate.

**References**