Initial Stability of Press-Fit Acetabular Components: An In Vitro Biomechanical Study

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Abstract

Component shape, surface finish, and presence of holes for adjuvant screw fixation should all affect initial stability and hence long-term fixation of total hip acetabular components.

We conducted a study to determine stability against edge loading and torsion in commercial implants that differed in these design variables.

Components were seated into synthetic cancellous bone blocks, and loads and insertion energies necessary to seat the components were measured. Components were then edge-loaded or twisted to failure.

Compared with several hemispherical components, an elliptical component without holes and sintered beads had significantly more stability under both loading conditions. The presence of more holes in hemispherical components significantly improved stability in edge loading but not in torsion. Finally, plasma-spray and small-bead coatings showed improved stability compared with fiber-mesh and large-bead coatings.

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Use of a porous metallic coating intended to allow bone ingrowth is the most common means for fixation of acetabular components in total hip arthroplasty.[1] Successful long-term biological fixation requires initial stability between implant and bone (with interfacial motions of less than 150 microns) and close opposition between the porous coating and the reamed bony surface of the acetabulum.[2,3] Early work in the 1980s by Harris and colleagues[4] and Hedley and colleagues[5] using canine models of total hip arthroplasty showed that bone growth into porous-coated acetabular components consistently occurred when surface contact was obtained on implantation of the acetabular component.

Several component designs (eg, cylindrical, square, conical, hemispherical, elliptical) and porous coatings (eg, cobalt alloy or titanium alloy beads, titanium fiber mesh, titanium alloy plasma spray) have been used to try to maximize fixation. Adjuvant fixation, in the form of threaded rings, holes (for secondary screw fixation), hooks, and flanges, has also been used for component stability.[1,6] Threaded and hemispherical acetabular components have emerged as the most widely used, though the efficacy of the threaded component remains questionable, with a report of 20% radiographic instability at a mean follow-up of 3.9 years in a series of 130 components.[7]

Despite the large number of shapes and materials that have been incorporated into acetabular component design, little is known as to which component shape, porous coating, or screw hole combination will maximize initial stability of the component and therefore achieve the best conditions for biological fixation.

Our objective in this study was to examine the initial mechanical stability of several commercial porous-coated components. We used an in vitro model in which polymeric foam simulated the cancellous bone in the acetabulum, thus minimizing the inherent variability in the properties of cadaveric bone. The designs were chosen to provide a range of shapes, coatings, and screw hole configurations. We sought to answer 3 research questions about initial fixation: Does an elliptical shape provide an advantage over a hemispherical shape? Is initial stability decreased in a component with screw holes versus a solid component without screw holes? How does type of porous coating affect initial stability?

MATERIALS AND METHODS

Six commercial components (Table I) were chosen to include 2 different shapes (elliptical, hemispherical), 2 different screw hole configurations (plus no screw holes), and 3 different types of porous coating. All components had an outer diameter of 56 mm. Synthetic cancellous bone block specimens approximately 76 mm per side were prepared from Pedilen foam (Otto Bock HealthCare, Minneapolis, Minn) with a density of 0.22 g/c^3, simulating medium-density cancellous bone.[8] Each block was reamed to a depth of 27 mm using a standard 54-mm hemispherical reamer mounted to a milling machine for all cup types. After reaming, a small hole was drilled through the pole of the resulting cavity; this hole was used to visualize the seating of the component during the subsequent insertion.

The foam blocks were secured to an aluminum base plate on the actuator of a servohydraulic test machine (MTS Bionix 858, Eden Prairie, Minn) using step blocks and clamps. The 56-mm-diameter components were press-fit into the underreamed blocks using a rectangular flat steel plate. A level was balanced on the rim of the components before and after insertion to ensure proper alignment.

A series of preliminary tests was conducted to establish the insertion conditions for the components. Each component was seated into a foam block under displacement control at 2.54 mm/s while the applied displacement that the component traveled during insertion and the load were continuously monitored. The rate of 2.54 mm/s was chosen a priori by the surgeons involved in the study as a close approximation of what typically occurs during total hip arthroplasty. Examination of the resulting plots of load versus displacement revealed that the load distinctly increased when the component was fully seated. The load at this insertion breakpoint (Table I) was then chosen as the maximum allowable load to be reached under displacement control when inserting the components for the subsequent edge-loading and torsion tests.

Initial stability in response to edge loading was determined by mechanically testing 60 specimens (10 of each of the 6 designs). Each component was inserted into a foam block under the conditions established in the preliminary tests. During insertion, load and displacement were recorded; *insertion energy* was defined as the area under the load versus displacement curve. Proper component seating was checked by inspection through the drill hole created in the pole of the cavity reamed in the block. With the foam block again secured to the actuator of the test machine, an impactor was secured to the load cell of the test system so that it would contact the outer diameter of the rim of the component. The 60 specimens were tested in random order. Initial stability was described from the load-versus-displacement curve (Figure) as *yield load* (using a line offset by 0.1 mm from the initial straight-line portion of the load vs the displacement curve), *ultimate load* (maximum load sustained by component before failure), and *ultimate energy* (area under load-displacement curve from start of test until ultimate load).

Initial stability was also determined under torsion loads. After insertion of an acetabular component into a foam block (using the same methodology used to insert components for the edge-loading tests), the block was secured to the actuator of the test machine, and a compressive preload of 2000 N (to simulate the load across the hip joint during stance) was applied by a metallic fixture used to interlock with the inner surface of the component. The fixture was then rotated at a rate of 0.035 radians/s until failure. The rate of 0.035 radians/s was chosen a priori by the team of investigators. Applied torque and rotational displacement were monitored continuously. As with the edge-loading

Table I. Cementless Acetabular Components (Outer Diameter of 56 mm in All Cases)

Component Design	Shape	Porous Coating	Holes	Insertion Load (N)
Continuum (Implex, Allendale, NJ)[a]	Elliptical	Small sintered beads	0	2890
Ranawat-Burstein (Biomet, Warsaw, Ind)	Hemispherical	Plasma spray	9	2670
RX-90 (low profile; Biomet, Warsaw, Ind)	Hemispherical	Plasma spray	3	1780
Ranawat-Burstein (Biomet, Warsaw, Ind)	Hemispherical	Plasma spray	0	1335
Trilogy (Zimmer, Warsaw, Ind)	Hemispherical	Fiber mesh	0	1780
Reflection (Smith & Nephew, Arlington, Tenn)	Hemispherical	Large sintered beads	0	2225

[a] Implex is now a subsidiary of Zimmer (Warsaw, Ind).

Table II. Insertion Energy, Yield Load, Ultimate Load, and Energy at Ultimate Load (Mean±SD)*

Acetabular Component	Insertion Energy (J)	Yield Load (N)	Ultimate Load (N)	Energy at Ultimate Load (J)
Continuum	6.20±0.66[a]	1256±155[a]	1542±253[a]	2.93±1.20[a]
Ranawat-Burstein (9 holes)	5.00±0.42[b]	1110±70[b]	1598±232[a]	2.85±0.75[a]
RX-90 (low profile)	4.27±0.74[b]	810±88[c]	1040±231[b]	1.54±0.70[b]
Ranawat-Burstein (no hole)	2.91±0.25[c]	693±94[c]	1255±152[b]	2.45±0.53[ab]
Trilogy	3.23±0.88[c]	799±106[c]	1068±206[b]	1.19±0.39[bc]
Reflection	3.27±0.32[c]	706±102[c]	748±119[c]	0.38±0.08[c]

*Within each column, [a] significantly greater than [b], [c], and [bc]; [b] significantly greater than [c]; [ab] not significantly different from [a] or [b] but significantly greater than [c]; [bc] not significantly different from [b] or [c].

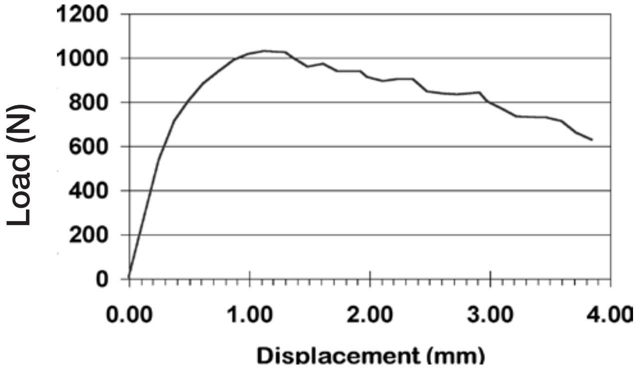

Figure. Load-versus-displacement curve for a hemispherical component with fiber-mesh coating. Yield load was determined from the intersection between the load-displacement curve and a line offset 0.1 mm from the initial straight-line portion of the curve. Ultimate load was determined as the peak load on the curve. Energy at ultimate load was determined from the area under the curve between the origin and the ultimate load.

tests, 10 components of each design were tested in random order. Maximum torque sustained before failure and total rotation to failure were used to describe initial stability.

Statistical Analyses

For each experiment, statistical analysis was performed with one-way analysis of variance. When significance was determined, individual designs were compared with the Tukey-Kramer comparison test. Alpha was set at $P<.05$.

RESULTS

Implant design significantly affected the energy required to insert the acetabular component (Table II). Hemispherical components without holes required less energy to insert than either hemispherical components with holes or the elliptical component ($P<.005$). The elliptical design with small sintered beads and no holes required the most insertion energy ($P<.005$).

Implant design also affected the mechanical stability of the acetabular components in resisting edge loading. In general, the elliptical design and the hemispherical component with the most holes exhibited the most stability, as exhibited by significantly higher yield and ultimate loads and higher energies to ultimate load, in comparison with other designs. No significant correlation was found between insertion energy and ultimate energy (r^2, 0.39).

Table III. Maximum Torque and Rotation to Failure (Mean±SD)*

Acetabular Component	Maximum Torque (NM)	Rotation to Failure (°)
Continuum	76.2±2.90[a]	5.7±2.58[a]
Ranawat-Burstein (9 holes)	72.2±9.05[a]	6.0±1.73[a]
RX-90 (low profile)	61.9±8.28[b]	4.7±1.49[ab]
Ranawat-Burstein (no hole)	72.9±5.50[a]	5.7±1.69[a]
Trilogy	57.8±2.87[c]	2.9±1.28[b]
Reflection	56.3±7.42[c]	2.4±0.81[b]

*Within each column, [a] significantly greater than [b] and [c]; [b] significantly greater than [c]; [ab] not significantly different from [a] or [b].

Type of porous coating did not significantly affect yield load measured under edge loading (Table II); among the hemispherical components, however, the bead coating was inferior to the plasma-spray and fiber-mesh coatings in terms of ultimate load and energy.

Stability of the acetabular components under torsional loading also depended on both component design and type of porous coating (Table III). As with the edge-loading results, the elliptical shape was among the most stable as measured both in torque and rotation to failure. Hemispherical components with plasma-spray coatings (Ranawat-Burstein with 9 screw holes and without holes) withstood significantly higher torques to failure than hemispherical components with porous coatings of large beads or fiber mesh (Reflection and Trilogy, respectively) and the low-profile hemispherical component with a plasma-spray coating and 3 holes (RX-90). Similarly, the hemispherical components with plasma-spray coatings (Ranawat-Burstein with 9 screw holes and without holes) and the elliptical component with a porous coating of small beads (Continuum) withstood significantly more rotations to failure than hemispherical components with porous coatings of large beads or fiber mesh (Reflection and Trilogy, respectively).

DISCUSSION

In this study, we examined several important design factors of contemporary commercial hip replacement acetabular components in terms of their impact on initial fixation as determined by in vitro mechanical testing. Component stability was characterized by mechanical resistance to edge loading, such as occurs during impingement or dislocation, and to torsional loading, such as results from friction across the joint bearing surfaces. To control for experimental variations that might occur with use of cadaveric acetabula and to reduce study time and cost, we substituted a foam material that mimics properties of human cancellous bone. We also controlled the geometry of the cavity into which the components were inserted and the outer diameter of the components in a further attempt to isolate design factors as the only variables that would influence differences in our test measurements.

Our results showed that design played an important role in initial fixation. In general, design factors that benefited initial fixation were elliptical shape, holes in metallic shell, and porous coating of plasma spray or small spherical beads. For example, in edge loading, the elliptical component had yield and ultimate loads more than 80% higher than those of the poorest hemispherical components, those with no screw holes and plasma-spray or large-bead porous coatings (Table II). In torsion, the elliptical component was 35% stronger than the poorest of the hemispherical components and withstood more than twice the rotational displacement before failure (Table III). The added permanent deformation created by the insertion of a component that does not match the geometry of the reamed cavity could account for this advantage.

Screw holes had a marked effect in increasing stability of hemispherical components in edge loading. The component with 9 holes had yield and ultimate loads and energies 16% to 60% higher than those measured in the component without holes. However, this advantage was not observed under torsional loading. The mechanical advantage of screw holes may be explained by the deformation of the foam into the screw holes on insertion, requiring added shear during the edge loading to disrupt the foam that had intruded into the screw holes. Lack of an effect in torsional loading probably resulted from the added compressive axial load, effectively increasing the friction across the component–foam interface for all component designs, overriding any effect of the holes.

Given that screw holes have been shown to be a pathway for particulate debris[9] contributing to osteolysis, use of screw holes simply to improve initial fixation may be unwarranted. Surgeons have abandoned screw fixation in the acetabulum with very acceptable clinical results.[10] A monoblock acetabular uncemented component has advantages in reducing failures as a result of a potential decrease in back surface polyethylene wear, elimination of locking rings that may generate metallic debris, and elimination of screw holes, which decrease the surface area for ingrowth and provide pelvic entrance points for wear debris.

Finally, the type of porous coating also affected initial stability of the acetabular components tested in our study. Titanium plasma spray was superior under torsion loading to both titanium fiber mesh and large cobalt beads in terms of both torque and rotation to failure (Table III). The plasma-spray coating also exhibited higher ultimate load and energy to failure under edge loading. These results can be explained by the higher coefficient of friction between the plasma-spray coating and the foam in comparison with that between the other coatings and the foam—consistent with the rougher surface and larger contact area.

We decided not to include screws for adjuvant fixation in our study. Screws might be expected to enhance initial stability, as has been shown in previous studies,[11,12] though underreaming has been found to have a similar beneficial effect.[13,14] Underreaming the acetabulum provides fixation through permanent deformation of the bone and subsequent recoil.[15]

Whereas the previous studies have emphasized the importance of underreaming and screw fixation, this study has demonstrated that initial fixation of acetabular components does not depend only on underreaming of the bone. Component geometry, presence or absence of screw holes, and surface finish are important and must be considered when choosing the appropriate acetabular component.

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This paper will be judged for the Resident Writer's Award.