The "Z-Effect" Phenomenon Defined: A Laboratory Study

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ABSTRACT: The Z-effect phenomenon is a potential complication of two lag screw intramedullary nail designs used for fixation of intertrochanteric hip fractures, in which the inferior lag screw migrates laterally and the superior lag screw migrates medially during physiologic loading. The current investigation was undertaken in an attempt to reproduce the Z-effect phenomenon in a laboratory setting. Sixteen different simulated femoral head and neck constructs having varying compressive strengths were created using four densities of solid polyurethane foam and instrumented with a two-screw cephalomedullary intramedullary nail. Each specimen was then cyclically loaded with 250 N vertical loads applied for 10, 100, 1000, and 10,000 cycles. Measurement of screw displacement with respect to the lateral aspect of the intramedullary nail was made after each cyclic increment. The inferior lag screw migration component of the Z-effect phenomenon was reproduced in specimens with head compressive strengths that were higher than the compressive strengths of the neck. Specimens with the greatest difference in head–neck compressive strength demonstrated the most significant displacement of the inferior lag screw without any displacement of the superior lag screw. Specimens with a femoral neck compressive strength of 0.91 MPa of and a head compressive strength of 8.8 MPa resulted in more than one centimeter of inferior lag screw lateral migration after 10,000 cycles of vertical loading. Models where the femoral head had a higher compressive strength than that of the femoral neck may simulate fracture patterns with significant medial cortex comminution that are prone to varus collapse.
Keywords: Z-effect; hip fracture; intramedullary nail; biomechanics

INTRODUCTION

Intertrochanteric hip fractures are common injuries in the elderly.[1–3] Options for the management of these fractures include extramedullary and intramedullary implants. In unstable fracture patterns, intramedullary devices appear to have a biomechanical advantage over extramedullary devices, lowering the forces imposed on the implant due to the shorter lever arm of the fixation.[2,4,5] Clinical studies have shown that certain intramedullary implant designs can develop complications, such as femoral shaft fracture below the tip of the device, femoral head screw cutout, and collapse at the fracture site.[2,6,7]

Intramedullary nails with two lag screws were designed to improve rotational control and bony purchase within the femoral head, thus resisting cutout and subsequent fixation failure.[8] Kubiak et al.[8] demonstrated that the two lag screw design provides equivalent rigidity and stability compared to an intramedullary nail with a single lag screw and has a significantly higher failure strength. This implant design, however, has led to the recognition of a new failure pattern—the Z-effect phenomenon—which manifests as collapse of the head/neck fragment resulting in protrusio of the superior lag screw and migration of the inferior lag screw lateral to the nail (Fig. 1).[2,9–11]

The Z-effect phenomenon, originally described by Werner-Tutshcku et al.[11] in their series of 70 proximal femur fractures managed with the Proximal Femoral Nail, has also been reported in subsequent case series.[2,9,10] Reported cases demonstrated penetration of the femoral head by the more superior antirotation lag screw with lateral migration of the more inferior lag screw, requiring implant removal. Although some authors have theorized that medial cortex comminution and varus positioning of the fixation contribute to the Z-effect, the exact etiology of the differential screw migration has yet to be determined. A

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Figure 1. Z-Effect phenomenon seen in an intertrochanteric hip fracture treated with the Trochanteric Antegrade Nail (Smith + Nephew, Memphis, TN). The proximal lag screw has penetrated the femoral head into the acetabulum, and the distal lag screw has migrated laterally.

reverse Z-effect has also been described in cases treated with two lag screw intramedullary nail designs, with lateral migration of the superior hip screw requiring implant removal.[9,10]

The current investigation was aimed at reproducing the Z-effect phenomenon in a laboratory setting, using an analog model in which the density and resultant compressive strength of the femoral head and neck could be varied in a controlled manner. The major assumption of the model is that the use of a low-density material as a surrogate for the femoral neck would have biomechanical properties similar to that seen in cases of intertrochanteric hip fracture with medial cortical comminution. The first research question was whether the combination of a high compressive strength femoral head component with a low compressive strength femoral neck component would create the differential screw migration of the Z-effect. We hypothesized that this combination of components would promote varus alignment at the fracture site during loading, a likely risk factor for the development of protrusio of the superior lag screw and lateral migration of the inferior lag screw. The second research question addressed was whether the opposite scenario, using a low compressive strength femoral head component and a high compressive strength femoral neck component, would lead to a reverse Z-effect with loading. We hypothesized that this reverse scenario of relative component compressive strength would lead to valgus alignment with loading and the opposite screw migration.

MATERIALS AND METHODS

An analog laboratory model was developed in which the head and neck of the femur could be separately fabricated from four different densities of Sawbones (Pacific Research Labs, Vashon, WA). Sixteen head–neck density combinations were created using solid, rigid, polyurethane foam Sawbones biomechanical testing blocks of 0.08, 0.11, 0.19, and 0.32 g/cc densities (Table 1). These have compressive strengths of 0.91, 2.2, 4.9, and 8.8 MPa, respectively, similar to the ranges seen in human cancellous bone.[12] Each combination was composed of a $6.0 \times 2.5 \times 2.5$-cm neck component and a $2.5 \times 2.5 \times 2.5$-cm head component glued together with a thin layer of high bond strength epoxy. The two lag screws of the trochanteric antegrade nail (TAN, Smith + Nephew, Memphis, TN) were inserted through the nail into the Sawbones head–neck specimens until the heads of the screws were 20 mm from the lateral aspect of the nail, to approximate the distance to the lateral cortex (Fig. 2a). One hundred-millimeter lag screws were utilized to ensure that the screw threads were entirely in the head fragment, with two new lag screws used for each tested specimen. The distal end of the nail was held in a rectangular stainless steel holder for biomechanical testing.

Mechanical evaluation of three specimens of each compressive strength combination (48 tested specimens) was then performed by securing the held implant–Sawbones construct in a vise with the nail at 25 degrees of adduction in the coronal plane and neutral in the sagittal plane to simulate one-legged stance.[13] An Instron 2000 Universal Material Testing Machine (Instron, Canton, MA) was used for loading, using a polished flat applicator to permit free movement of the head when loaded. Specimen ends (simulated head) were beveled to ensure a flat area of contact (1 cm^2). Displacement measurements included the determination of the distance from the center of the head of each lag screw to the lateral aspect of the associated screw hole in the shaft of the nail, using a digital caliper with a resolution of 0.005 mm and an accuracy of 0.01 mm (Avenger 6″ Digital Caliper, Boulder City, NV). Each specimen was then

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Table 1. Lag Screw Migration with Cyclic Loading

Simulated Femoral Head and Femoral Neck Construct (MPa)	Mean Inferior Lag Screw Migration (mm) after 10,000 Loading Cycles (3 Specimens per Compressive Strength Combination)	Mean Superior Lag Screw Migration (mm) after 10,000 Loading Cycles (3 Specimens per Compressive Strength Combination)
0.91 Head/0.91 Neck	0.30	0.16
2.2 Head/0.91 Neck	1.60	0.20
4.9 Head/0.91 Neck	6.20	0.24
8.8 Head/0.91 Neck	11.01	0.24
0.91 Head/2.2 Neck	0.20	0.20
2.2 Head/2.2 Neck	0.19	0.16
4.9 Head/2.2 Neck	1.75	0.22
8.8 Head/2.2 Neck	2.66	0.12
0.91 Head/4.9 Neck	0.20	0.10
2.2 Head/4.9 Neck	0.20	0.10
4.9 Head/4.9 Neck	0.17	0.08
8.8 Head/4.9 Neck	0.80	0.08
0.91 Head/8.8 Neck	0.10	0.08
2.2 Head/8.8 Neck	0.10	0.06
4.9 Head/8.8 Neck	0.10	0.06
8.8 Head/8.8 Neck	0.09	0.06

initially loaded with 250 N and allowed to come to equilibrium (120 s) before displacement measurements were made. Next, each specimen was cyclically loaded, with 250 N vertical loads applied at a rate of 3 Hz for 10, 100, 1000, and 10,000 cycles. Three specimens of each density combination were tested. Each specimen was allowed to reach equilibrium (120 s) after each cyclic interval, and lag screw displacements were measured.

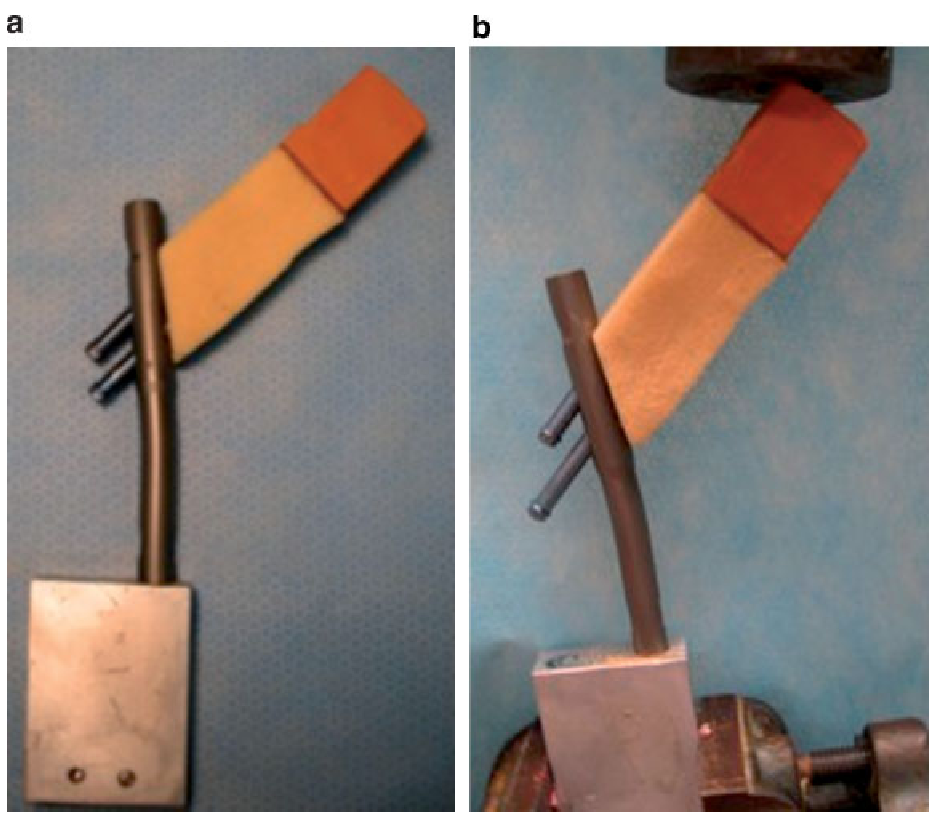

Figure 2. (a) TAN–Sawbones construct (neck component of 0.91 MPa compressive strength and head component of 8.8 MPa compressive strength). (b) Application of a vertical load resulted in varus angulation of the implant–neck/head interface. Cyclic loading led to 11 mm of lateral migration of the inferior lag screw after 10,000 cycles.

Unpaired Student t-tests were used for statistical analysis of the screw displacements for each femoral head and neck density combination. A p-value of <0.05 was considered to be statistically significant.

RESULTS

Cyclic vertical loading of specimens with equal femoral head and neck compressive strengths did not result in appreciable migration of the inferior lag screw after 10,000 cycles ($p < 0.9$ for all comparisons). Specimens with head and neck components with 8.8 MPa compressive strength (0.32 g/cc density) demonstrated a mean of less than 0.1 mm of inferior lag screw lateral migration after 1000 and 10,000 cycles at 250 N. Specimens with components of 4.9 MPa and 2.2 MPa (0.19 g/cc and 0.11 g/cc densities, respectively) showed <0.2 mm of lateral migration after 1000 and 10,000 cycles, and specimens with head and neck compressive strengths of 0.91MPa (0.08 g/cc density) resulted in mean distal screw migration of 0.3 mm (Table 1).

Cyclic vertical loading of the femoral head–neck constructs with head components that had greater compressive strength than the neck components reproduced the lateral migration of the inferior lag screw component of the Z-effect (Fig. 2b). The greater the difference in compressive strength, the greater the displacement of the inferior lag screw with cyclic loading ($p < 0.001$ for each comparison of head compressive strength with decreasing neck compressive strength; Fig. 3) The least displacement occurred in constructs composed of a neck of 4.9 MPa (0.19 g/cc density) and a head of 8.8 MPa (0.32 g/cc density) with a mean lateral migration of the inferior lag screw of 0.6 mm after 1000 cycles of loading and 0.8 mm after 10,000 cycles. The greatest amount of inferior lag screw migration was observed in constructs with the lowest compressive strength neck components. Specimens with 0.91 MPa necks and 4.9 MPa and 8.8 MPa heads demonstrated 3.4 and 5.3 mm of inferior lag screw migration after 1000 cycles at 250 N and 6.2 mm and 11.0 mm of migration after 10,000 cycles, respectively (Fig. 3).

Superior lag screw penetration through the superior aspect of the head component was seen in all of the specimens with head component compressive strength of 0.91 MPa (0.08 g/cc density) and in one specimen with a head component compressive strength of 2.2 MPa (0.11 g/cc density) (Fig. 4). The amount of penetration was limited by contact with the loading plate. Screw

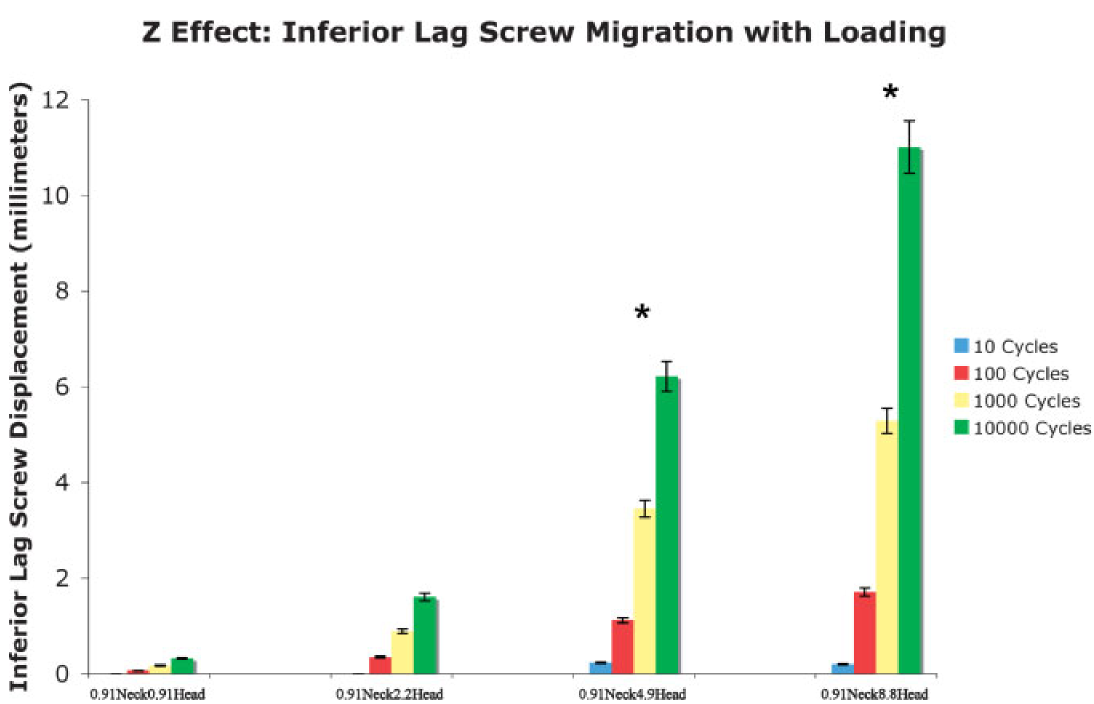

Figure 3. Lateral migration (mm) of the inferior lag screw for simulated femoral head and neck compressive strength combinations in which the neck component had a compressive strength of 0.91 MPa. The greatest amount of inferior screw displacement occurred in specimens with the greatest difference in compressive strength between the simulated femoral head and femoral neck. *Denotes significant difference in screw migration between head and neck density combinations after both 1000 and 10,000 loading cycles ($p < 0.001$).

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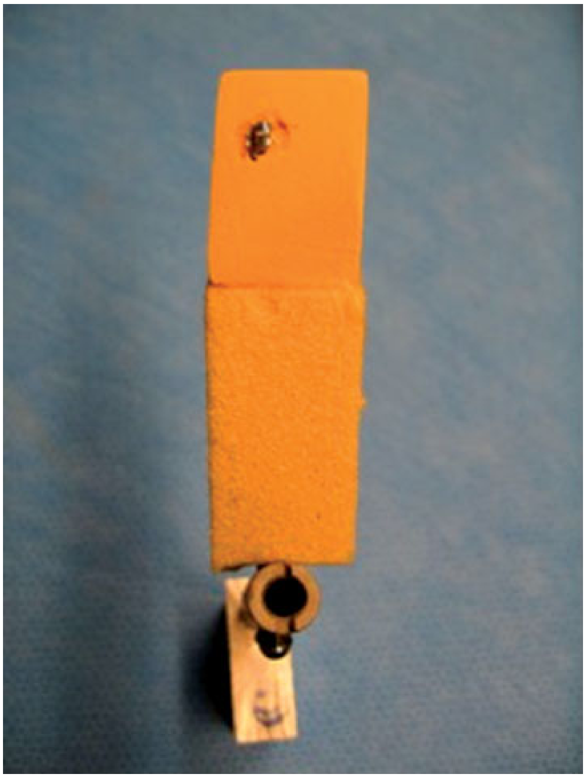

Figure 4. Penetration of the superior aspect of the specimen head component by the superior lag screw after 10,000 cycles of vertical loading. Superior lag screw penetration was observed in all three specimens whose head components had a compressive strength of 0.91 MPa heads and in one specimen with a 2.2 MPa head.

penetration was not observed in those specimens with head compressive strengths of 4.9 and 8.8 MPa (densities of 0.19 and 0.32 g/cc). Penetration was observed after 1000 cycles, but was most significant after 10,000 cycles.

The reverse Z-effect, defined as a lateral migration of the superior lag screw and a medial penetration of the inferior lag screw, was not observed after cyclic vertical loading of specimens with femoral neck compressive strengths that were greater than that of the femoral head. Mean lateral migration of the superior lag screw was <0.06 mm in specimens with neck compressive strengths of 8.8 MPa (density of 0.32 g/cc) and heads of 0.91, 2.2, and 4.9 MPa (0.08, 0.11, and 0.19 g/cc densities, respectively). Screw displacement of <0.10 mm was seen after cyclic loading of specimens with neck compressive strength of 4.9 MPa (density of 0.19 g/cc) and heads of 0.91 and 2.2 MPa (0.08 and 0.11 g/cc densities, respectively). No significant difference were found between construct head and neck combinations with respect to superior lag screw migration ($p > 0.9$ for all comparisons).

DISCUSSION

We found that the inferior lag screw migration component of the Z-effect phenomenon could be reproduced in a laboratory setting using an analog model in which the density and resultant compressive strength of the femoral head and neck could be varied. Specimens in which the compressive strength of the head was greater than that of the neck allowed for lateral migration of the inferior lag screw. Inferior lag screw migration was greatest for specimens with the largest compressive strength difference between the head and neck and increased with increasing number of loading cycles. Screw migration was not observed in specimens with equal head and neck compressive strength. Penetration of the superior lag screw through the head component was seen in specimens with lower head compressive strength, but not in those with higher head compressive strength. The reverse Z-effect was not seen in models where the compressive strength of the neck was greater than that of the head.

During specimen testing, we observed that vertical loading forced the implant–Sawbones construct into a varus position (range of 12–21° as measured with a goniometer). Additionally, the lower the compressive strength of the femoral neck component, the greater the varus alignment (mean of 19° and 21° in specimens with 2.2 and 0.91 MPa neck components, respectively). This varus positioning typically facilitates sliding of both of the proximal lag screws, creating fracture site compression during the initial phases of physiologic loading, which occurs with postoperative mobilization.[14] However, we believe that when the construct is forced into the varus, the bending loads on the lag screws are unequal. Even though both screws are engaged superiorly within the uniform density head material, the superior screw bends, which locks it in place within the medial aspect of the proximal hole of the nail, as evidenced by a uniform indentation seen on the superior lag screw at this position during inspection after loading (Fig. 5).

We have looked at a simple, two-dimensional finite element analysis that indicates the importance of bone density between the screws as being important for independent mechanical behavior of the two screws. In cases where the density and resultant compressive strength of the neck is significantly lower than that of the head, a situation which may be seen with unstable fracture patterns with significant medial cortical comminution, the combination of superior lag screw

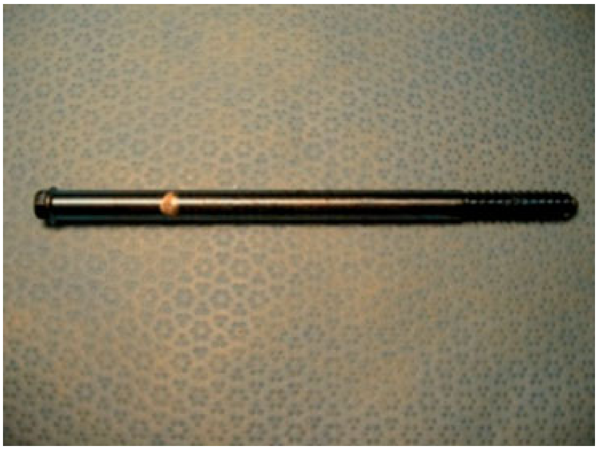

Figure 5. Indentation of the superior lag screw observed in the region of the medial screw hole during loading.

engagement in the nail, lack of bony purchase in the neck, and toggle of the inferior lag screw from repetitive loading causes the inferior lag screw to migrate laterally. Continued vertical loading and increased varus forces on the superior, locked screw in the head may eventually lead to femoral head penetration.

Limitations of the current study include the use of polyurethane foam Sawbones biomechanical testing blocks to simulate the actual femoral neck and head. Using the testing blocks allowed us to control and observe the effect of differing densities and resultant compressive strength of the head and neck components had on the development of the Z-effect phenomenon. However, this model may not accurately represent the in vivo clinical situation, as there is a gradual transition of density from inner trabecular bone to outer cortex within the proximal femur. Our ability to detect medial migration of the superior lag screw with loading may have been limited by our testing setup, with the load applicator restricting displacement. Additionally, our model used only one type of two lag screw intramedullary nail design, and the models were only loaded axially and not in torsion, which could also be a risk factor for the development of the Z-effect. Future studies should include testing other two lag screw intramedullary nail designs and reproducing our testing conditions in a cadaveric unstable fracture pattern model.

We were able to reproduce the inferior lag screw component of the Z-effect phenomenon by varying the compressive strengths of the femoral head and neck and hence their stability. Physiologic loading created a situation where the fracture site was forced into a varus alignment. In models where the femoral head had a higher compressive strength than that of the femoral neck, simulating unstable fracture patterns with significant medial cortex comminution, screw migration led to a serious failure of fixation. In cases of significant medial cortical comminution, surgeons may wish to avoid the use of two lag screw intramedullary nail designs for the treatment of intertrochanteric hip fractures.

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